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Revision 1

Criticality Safety Study of the Subsurface Disposal Area for Operable Unit 7-13/14

Paul J. Sentieri
J. Todd Taylor

February 2003

Idaho National Engineering and Environmental Laboratory
Bechtel BWXT Idaho, LLC

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Idaho National Engineering and Environmental Laboratory
Environmental Restoration Program
Idaho Falls, Idaho 83415

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Approved by

Paul J. Sentieri Criticality Safety Engineer Author	2/12/03 Date
J. Todd Taylor Criticality Safety Department Manager Author	2/12/03 Date
Theodore J. Meyer OU 7-13/14 RI/FS Project Engineer	2-12-03 Date
David E. Wilkins Operable Unit 7-10 Deputy Project Manager	2-12-03 Date

ABSTRACT

The purpose of this document is to address the potential for a criticality in the Subsurface Disposal Area (SDA) by evaluating postulated configurations of waste matrices of concern. A criticality safety study was performed to address issues relating to postulated criticality scenarios in the SDA for Operable Unit 7-13/14 in the Radioactive Waste Management Complex at the Idaho National Engineering and Environmental Laboratory. The study evaluates the parameters that affect reactivity and demonstrates how these parameters ensure subcriticality of the SDA.

Based on the results of this study, a criticality is not credible with the expected fissile masses and waste forms in the SDA. The fissile material buried with waste in the SDA is not in a form and distribution that lends itself to criticality in a believable or feasible manner.

The revision to this study was performed to incorporate new information resulting from assay of aboveground transuranic waste drums, which has determined no drum to contain an unsafe mass of fissile material.

EXECUTIVE SUMMARY

The purpose of this document is to address the potential for a criticality in the Subsurface Disposal Area (SDA) by evaluating postulated configurations of waste matrices of concern. A criticality safety study was performed to address issues relating to postulated criticality scenarios in the SDA for Operable Unit 7-13/14 in the Radioactive Waste Management Complex at the Idaho National Engineering and Environmental Laboratory. The study evaluates the parameters that affect reactivity and demonstrates how these parameters ensure subcriticality of the SDA.

As shown by the study, a postulated criticality in the SDA is dependent on known parameters that affect criticality. These parameters include the amount of fissile mass and moderator present, the geometry of the configuration, the presence of diluents or neutron absorbers, reflection surrounding the fissile systems, and the concentration or distribution of the fissile material in the waste. Most of these parameters would have to be optimized in some combination to achieve a critical system. As deviations from optimum conditions occur, the reactivity of the systems decreases dramatically.

Models were developed that evaluated three individual types of waste matrices: high-efficiency particulate air (HEPA) filters, graphite, and MgO. These waste matrices were chosen mainly because they have been identified as having higher fissile loadings in aboveground and belowground waste. The HEPA-filter matrix was also chosen because it has the potential for a configuration with little diluent, and graphite because it is a good moderator. The effects of varying each of the parameters affecting criticality discussed above were evaluated in each of the models. This was done to examine the reactivity effect as the various parameters were permutated. Once the effects are understood, an analysis can be made for how these permutations could be related to expected real-world configurations. Most of these models are not realistic and the optimized assumptions cannot occur in actual waste configurations, but were constructed to show the effect of each factor.

The effect of having fissile mass present is rather straightforward and well understood. The more mass present (in general), the more reactive the system becomes. When a moderator is introduced into the system in near-optimum amounts, less fissile mass is required to postulate a critical configuration. Models were developed to show the effects of water in each of the three waste matrices. In addition, a set of models consisting of filter arrays loaded with lower, more realistic fissile material loading was evaluated to show the effects of fissile mass in that specific configuration.

The effects of geometry on the fissile systems were evaluated in various model permutations. Models were evaluated where filters were separated by different amounts of soil to determine the effects of spacing on reactivity. As expected, when spacing increases, the reactivity of the system decreases. The effects of homogeneity versus heterogeneity were evaluated in models involving both filters and graphite waste types. As expected, when the fissile material distribution becomes less optimized and less homogeneous, the reactivity of the system decreases.

The effects of various neutron absorbers and diluents were evaluated in different models. In one case, the effects were evaluated for boron being present in the soil and becoming soluble, thus intermixing with the fissile material and the filter. In another case, the effects of soil intermixing with the fissile material in the filter were evaluated. As expected, when the moderator was excluded in the filter structure, as a result of soil presence, the reactivity of the system decreased. The effects of boron in the native soil in the SDA were somewhat limited because of the small fraction of resident boron.

Reflection was evaluated by modeling a case in which the filter and fissile material system were both near optimum moderation with the soil surrounding the system being void of water. The lack of water in the reflecting layer increased the neutron leakage away from the fissile system. When compared with a similar fissile system containing a fully saturated soil reflector, the reactivity of the system lacking water in the reflector yielded a much lower calculated effective multiplication factor.

The concentration or distribution of the fissile material is another parameter that affects the reactivity of a particular system. As expected, the study showed that as the fissile material is diluted over a large volume at low concentration, the reactivity of the system decreases to a point where a critical system is not possible.

Based on the results of this study, a criticality is not credible with the expected fissile masses and waste forms in the SDA. The fissile material buried with waste in the SDA is not in a form and distribution that lends itself to criticality in a believable or feasible manner.

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ACRONYMS

HEPA	high-efficiency particulate air filter
INEEL	Idaho National Engineering and Environmental Laboratory
k_{eff}	effective multiplication factor
RFP	Rocky Flats Plant
RWMC	Radioactive Waste Management Complex
SDA	Subsurface Disposal Area
wvf	water volume fraction

Criticality Safety Study of the Subsurface Disposal Area for Operable Unit 7-13/14

1. INTRODUCTION

The purpose of this document is to address the potential for a criticality in the Subsurface Disposal Area (SDA) by evaluating postulated configurations of waste matrices of concern.

An criticality safety study was performed for the SDA, which is located in the Radioactive Waste Management Complex (RWMC) at the Idaho National Engineering and Environmental Laboratory (INEEL). It supports the Operable Unit 7-13/14 comprehensive remedial investigation/feasibility study implemented under Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) for Waste Area Group 7. Waste Area Group 7 is the designation recognized under the Federal Facility Agreement and Consent Order (DOE-ID-1991) and CERCLA for the RWMC. A map of the location of the RWMC at the INEEL is provided in Figure 1.

This study addresses postulated criticality scenarios in the SDA. The study evaluates the parameters that affect reactivity and demonstrates how these parameters ensure subcriticality of the SDA. Specifically, this criticality safety study was performed to determine postulated configurations and the related calculated effective multiplication factors (k_{eff}s) of fissile material buried in the SDA. The configurations evaluated in this report are based on different factors including conservative estimates, best available data, and engineering judgment. The lack of specific historical data relating to configurations and distribution of fissile material in the SDA leads to some of the conservative assumptions and engineering judgment used in this report.

The parameters affecting criticality in a fissile system include the (1) mass of fissile material present, (2) presence of moderating material, (3) geometric configuration, (4) presence of diluents and neutron absorber material, (5) reflection conditions around the system, and (6) concentration and distribution of the fissile material in the waste. Each of these parameters and the effects they have on reactivity will be evaluated in later computational models. Appendix A contains spreadsheets showing the mathematical calculations that produced the input parameters used in the computational models. Appendix B shows in tabular form the soil composition and input parameters that were used in the computational models.

The three waste forms containing fissile material that were evaluated in this study include high-efficiency particulate air (HEPA) filters, graphite, and magnesium oxide (MgO). These waste matrices were chosen mainly because they have been identified as having higher fissile loadings in aboveground and belowground waste. The HEPA-filter matrix was also chosen because it has the potential for a configuration with little diluent, and graphite because it is a good moderator. Evaluation of these matrices will envelop other waste types in the SDA.

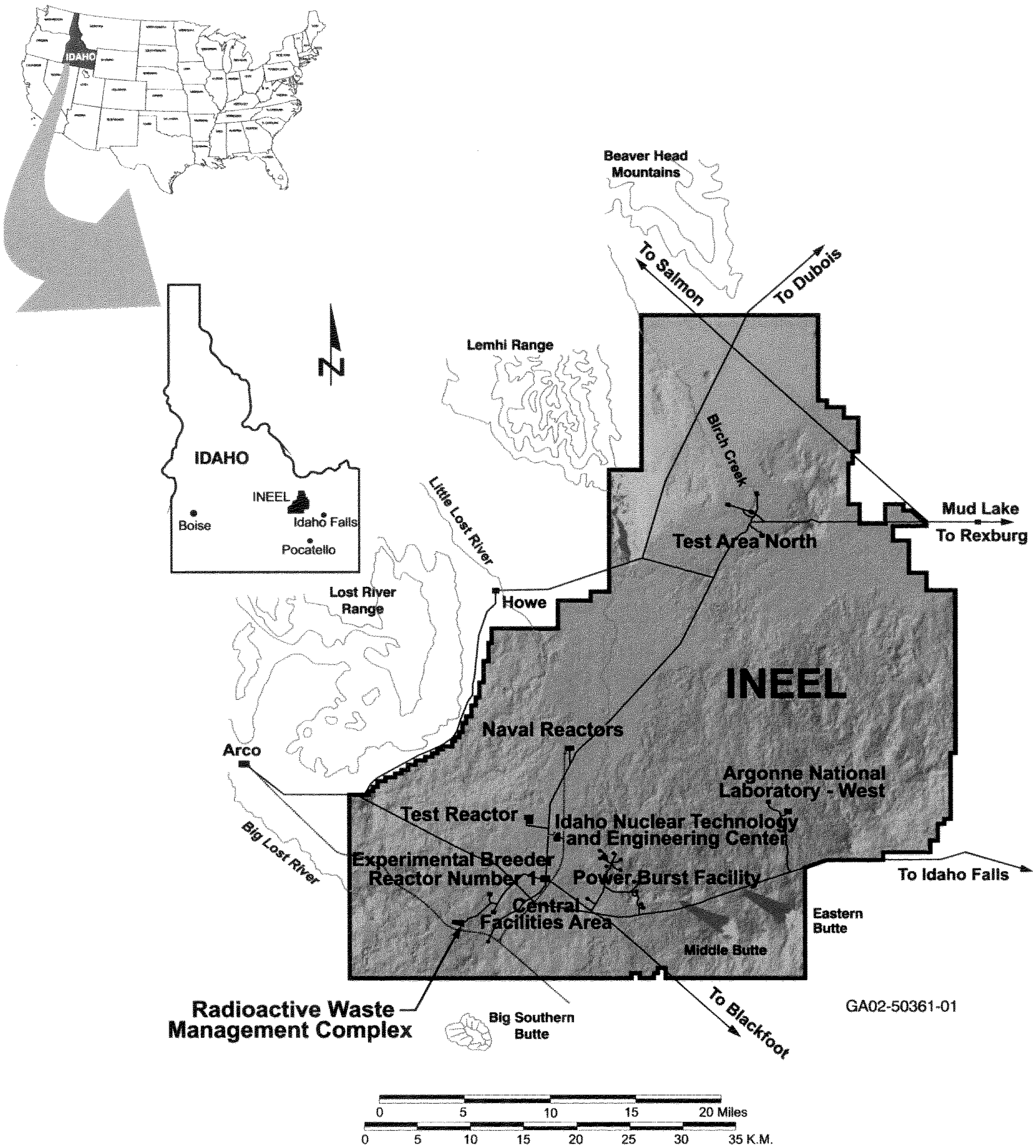

Figure 1. Map of the Idaho National Engineering and Environmental Laboratory showing the location of the Radioactive Waste Management Complex and other major facilities.

Sludge was not considered because the forms of the sludge are inherently subcritical and the historically low fissile loading in the sludge matrices. Sludges prohibit the optimum conditions required for the formation of a critical system because they contain diluents, significant absorbers and have low void volumes. Most of the sludge matrices contain a large amount of CCl_4. Chlorine is an excellent neutron absorber that effectively lowers the reactivity of a system by removing neutrons through parasitic absorption.

Several concurrent parameters must exist for a critical configuration to occur. For example, enough fissile mass must be present in the system. In an optimally moderated and near-optimally configured fully reflected system, the fissile mass necessary to achieve a critical system is about 520 g of Pu-239 mixed with water. The mass increases exponentially for a dry system consisting of PuO_2. Moderating material must be present and sufficiently mixed with the fissile material or the mass necessary to achieve a critical system will exceed the localized fissile mass expected in the SDA. In addition, the geometrical configuration must be near the optimum state. The fissile material must be distributed in a matrix lacking other materials that dilute the system or act as neutron absorbers. Lack of moderating material or the presence of diluents increases the mass needed to achieve a critical system.

The distribution or concentration of the fissile material in the waste buried at the SDA is not certain, but information is known of the waste streams that generated the waste. If the waste were packaged in accordance with the established limits, then the waste forms would remain subcritical even under fully moderated conditions. No near term postulated mechanisms exist to preferentially concentrate plutonium in the SDA. In addition, the likelihood of multiple overloaded drums being placed in adjacent positions in the SDA is very low. Under realistic conditions, achieving a critical system would be very difficult even in a grossly overloaded drum. Waste packages composed of wood or cardboard are known, from past retrieval operations, to have little or no structural integrity, thus precluding the accumulation of moderator.

Subsidence events at the SDA lend additional data that the buried waste containers and waste forms at the facility are being compressed by the overburden because of the degradation occurring in the buried waste. The degradation of the waste packages leads to the intermixing of soils more intimately with the waste forms and fissile material, thus increasing the subcriticality of the SDA and the mass necessary to achieve a critical system.

In addition, probing operations in which Lexan tubes were placed into the various waste matrices indicate deformation of the waste drums that housed the buried waste (Josten 2002). As in the case of the wooden and cardboard boxes, when the drums physically degrade, soil will be intermixed into the waste matrices with the fissile material.

No criticality concerns would exist if the buried waste complied with the 200-g limit of fissile material per drum and the box limit of less than 5 g of fissile material per cubic foot, with a total gram loading not to exceed 350 g per box. The fissile material would be sufficiently distributed such that it would be subcritical even under optimally moderated conditions. There has been concern of overloaded drums in the SDA, which was primarily based on early RWMC assay data of aboveground waste drums from the RFP. Later assay of drums with methods better suited for the waste matrices of concern has shown no drum to contain an unsafe mass of fissile material (greater than 380 g).

Calculated k_{eff}s associated with unrealistic postulated configurations were determined in this study. Although unrealistic, these calculations are useful to demonstrate the reactivity effects between conservative model configurations and the expected actual realistic configurations in the waste buried in the SDA. Calculations incorporating idealized conservatisms into the modeled systems will obviously result in very reactive k_{eff}s. These models are generally very ordered and represent configurations that would not be expected in the actual waste forms. Calculations presented here do not represent the reactivity of the buried waste, but show that as the systems deviate from these ordered systems, reactivity readily decreases. Various configurations were evaluated to demonstrate the effects of the factors previously outlined.

In short, a criticality is not credible in the SDA with the expected fissile masses and waste forms. Fissile material is mixed with the buried waste in the SDA, though not in a form and distribution that lends itself to criticality in a believable or feasible manner.

A flow diagram of the logic used in this report is shown in Figure 2. This figure is a pictorial representation of the methodology and logic used to determine k_{eff}s for the selected waste matrices in the postulated configurations. Appropriate sections and the associated tables outlining model descriptions and results are identified on the flowchart to aid in understanding the logic used in this analysis. As identified in the flowchart and demonstrated in the computational modeling, all of the evaluated base-case configurations remained subcritical.

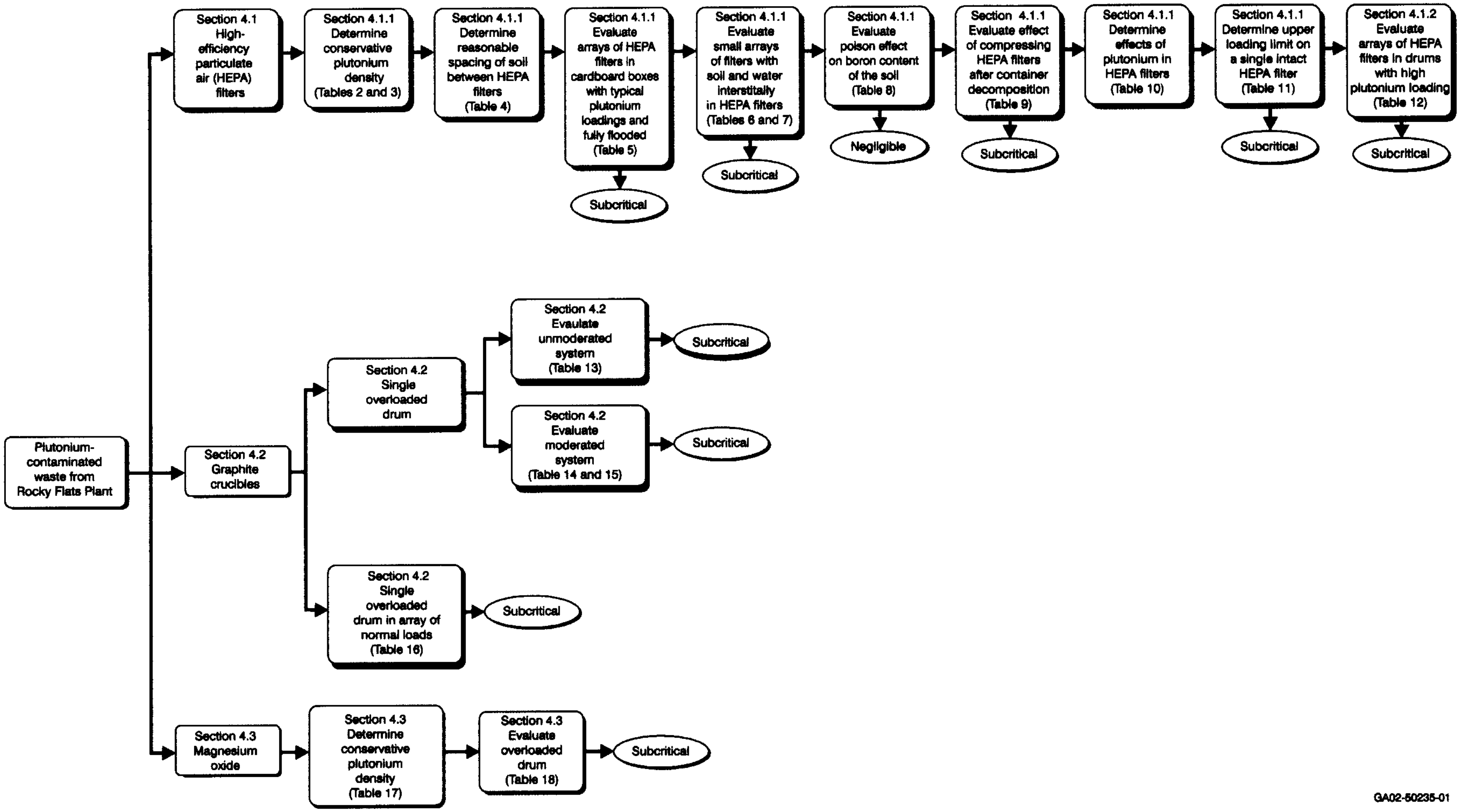

Figure 2. Flowchart of the criticality safety study for the Subsurface Disposal Area, Operable Unit 7-13/14.

2. BACKGROUND

The SDA is a 39.2-ha (96.8-acre) tract of land, as shown in Figure 3, located in the western portion of the RWMC at the INEEL on the Snake River Plain of southeastern Idaho (see Figure 1). The SDA is used to dispose of radioactive waste material in underground pits, trenches, soil vault rows, and similar structures. The SDA contains drums and waste boxes of plutonium-contaminated waste from the Rocky Flats Plant (RFP).[a] The thickness of the overburden is 0.9 to 1.8 m (3 to 6 ft). The trenches are approximately 2 m (7 ft) wide, 275 m (902 ft) long, and an average of 4 m (13 ft) deep. The pits are 30 m (98 ft) wide, 4 to 10 m (13 to 33 ft) deep, and vary in length from 60 to 360 m (197 to 1,181 ft).

Most of the waste contained in the SDA was received from RFP. Because of the mission of the RFP, the waste consists of plutonium-contaminated material. The waste in the SDA is buried and for the most part has been buried for more than 30 years. Before being shipped from RFP, the fissile mass of a single container was limited to 200 g of plutonium in the case of drums and 350 g of plutonium in the case of large wooden storage boxes. Whether these limits were adhered to in past operations, when waste drums were loaded at the waste-generating location, came under question because of potential overloaded-drum issues in the aboveground storage area of the RWMC. These concerns have since been determined to not be an issue as no drum has been found to contain an unsafe mass of fissile material. Approximately 20,000 drums from aboveground storage operations at the RWMC have been assayed for fissile content utilizing several nondestructive assay methods. Results from the assaying of these 20,000 drums show no drum has a fissile loading in excess of 380 g. About 100 drums have fissile loadings in excess of 200 g.

Because plutonium is a valuable commodity, efforts were made at RFP to recover as much as possible from the waste material before shipment for disposal. Even though the assaying methods used by RFP to meet the fissile-material limits for shipment to the INEEL were not as advanced as current assaying methods, a concerted effort was made to recover as much plutonium as possible from process waste. However, because there is a possibility an overloaded drum or box may be in the SDA, the consequence of such a package must be addressed.

Three waste matrices were identified from the various identified waste streams received from RFP as possible matrices of concern based on historical generator and assay data. These waste matrices include glovebox high-efficiency particulate air (HEPA) filters, graphite, and MgO.

The first type of waste matrix evaluated was HEPA filters. Variously sized HEPA filters were used in different capacities over the RFP operating history. Historical data[b] indicate that the first- and second-stage glovebox HEPA filters had a higher fissile loading than those used in the final-stage building air outlet plenums. This makes sense because the purpose of a filter is to remove particulate matter from a system. The geometrical configuration of the filters and the higher fissile loading that could be present make this waste matrix a logical choice for evaluation. Therefore, the greater the number of filters in-line, the less accumulation would be expected on the final-stage filters. The first- and second-stage filters were smaller filters that were housed near the process gloveboxes. The first-stage filters were located at the air outlet from the glovebox and the second stage filters were located not far down the ventilation line. A more detailed description is contained in the sections pertaining to the models developed for these filters.

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a. Rocky Flats Plant, located 26 km (16 mi) northwest of Denver was renamed the Rocky Flats Plant Environmental Technology Site in the mid-1990s. In the late 1990s it was again renamed, to the Rocky Flats Plant Closure Project.

b. D. E. Kudera, Interdepartmental Communication to W. H. Sullivan, March 28, 1994, “Historical Rocky Flats Plant Information on Plutonium Losses to Burial,” DEK-04-94, Idaho National Engineering and Environmental Laboratory, Lockheed Martin Idaho Technologies Company, Idaho Falls, Idaho.

The filters are of concern because some of the filters are known from past historical process data to have high fissile content. This high fissile content is estimated to be about 200 g of plutonium in a single first-stage filter. The nature of the HEPA filters would give a rather ordered array of layers of plutonium deposited on the filter media. If moderated by water, a large number of filters in an ordered array could yield calculated k_{eff}s that are high. Various configurations and arrays containing different constituents were analyzed. The results from these cases and a description of the configurations can be found in the evaluation and results section in this report.

The second type of waste matrix evaluated was plutonium intermixed with graphite. Graphite is also a byproduct from past production operations at RFP. This waste matrix was chosen because known overloading of these types of drums has occurred at RFP in the past (see footnote b). In addition, graphite is known for its moderation properties, which make this type of waste a logical candidate for investigation. Critical systems comprising fissile material and graphite generally are known to be very large in size with large graphite and fissile masses.

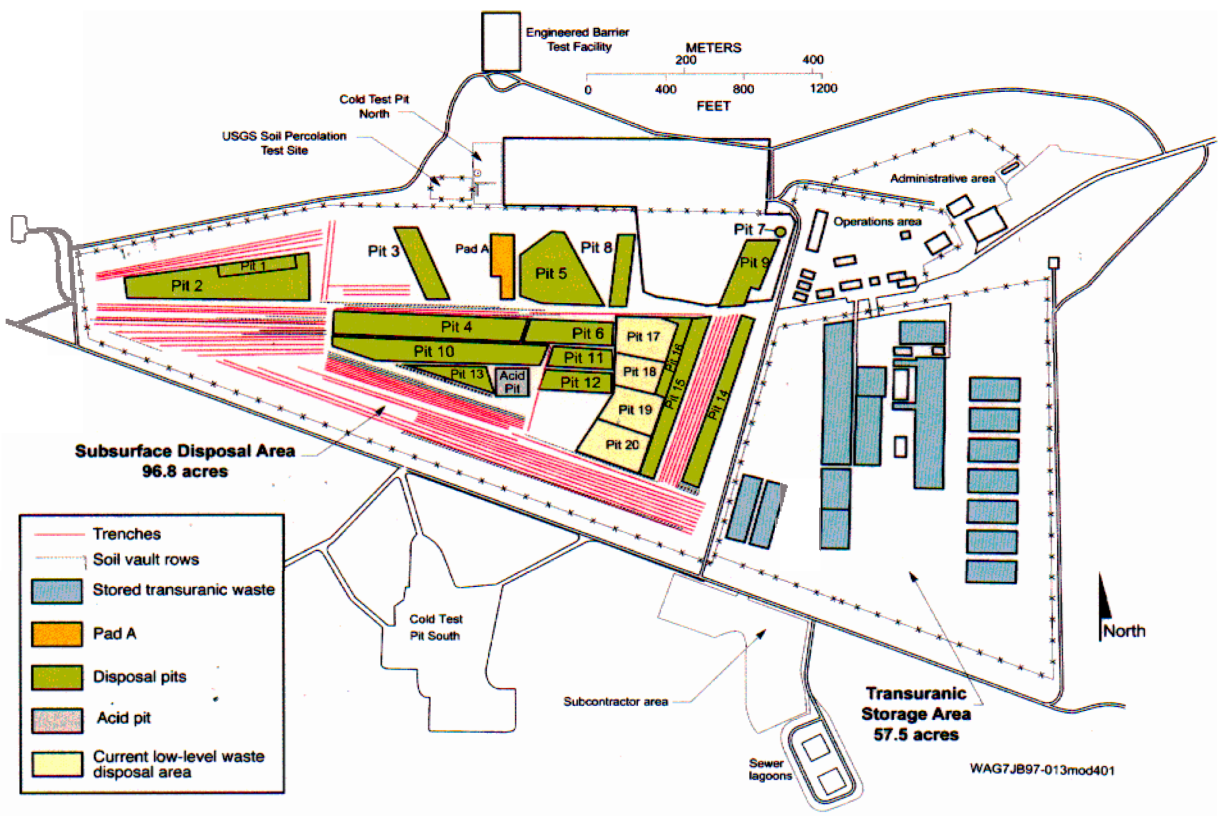

Figure 3. Subsurface Disposal Area at the Radioactive Waste Management Complex showing pits, trenches, and soil vault rows.

The third type of waste matrix evaluated was plutonium intermixed with MgO. Magnesium oxide is a byproduct of production lines that were in use at the RFP site. Initial assay of aboveground drums at the RWMC determined that eight MgO waste drums were overloaded (Woods and Neeley 2001). These drums have since been reassayed and shown to contain less than 200 g of plutonium. Although no overloaded drums of this waste type have been found, k_{eff} was evaluated for various configurations of MgO and plutonium.

Any plutonium metal, other than large pieces, will have undergone oxidation so that its form will be PuO_2. A large single piece of metal or a small grouping of larger pieces of metal with a fissile material loading in the range of the expected mass is not a criticality issue because the heterogeneous distribution of plutonium would lead to a system with a lower reactivity than the homogeneous models that were evaluated. Therefore, the plutonium was modeled as PuO_2 in all of the cases. The PuO_2 was modeled with a plutonium isotopic composition of 95% Pu-239 and 5% Pu-240. This isotopic distribution envelops the isotopic distribution of weapons-grade plutonium that could be in RFP waste.

The modeling composition of the soil used in the various cases (Callow et al. 1991) is listed in Appendix B (see Table B-1). Variations in the soil density and water content were evaluated for these configurations.

3. METHODOLOGY

All calculations listed in this report were performed using MCNP-4b2 (see Appendix C) with the ENDF/B-V (RSIC 1997) point-wise continuous energy neutron cross-section library. The computational platform consisted of Hewlett-Packard workstations using the HP-UX 10.20 operating system.

Because criticality limits are not being developed for implementation by this study, comprehensive validation work will not be addressed. Criticality in the SDA would require moderation and one can say that the moderated systems evaluated here have been well validated, and an adequate number of experiments exist that could be used to validate calculations performed here.

A set of critical experiments involving SiO_2, polyethylene, and highly enriched plutonium was conducted at the Institute of Physics and Power Engineering, in Obninsk, Russia, at the Big Physical Stand. This set of critical experiments covered a wide range of neutron spectra with fission ranging from thermal to intermediate. The critical assembly consisted of plutonium metal ingots, SiO_2 discs, and polyethylene discs that were placed into sets of aluminum tubes. These tubes then were arranged to form a critical configuration. A full description of these experiments can be found in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (OECD 2001). Computational verification of the critical configuration is included in this handbook. Joseph Nielsen (2002a) evaluated these experiments, and determined that the calculated values were in good agreement with the measured values from the experiment.

The calculations performed in this study show that the most reactive configurations exist with the postulated scenarios of intact water-flooded (solution-like systems) HEPA filters and other water moderated matrices. Critical experiments that involve plutonium and nitrate solution systems are also described in the *International Handbook* (OECD 2001). Most of these critical systems comprise both reflected and unreflected $PuNO_3$ solutions in spherical and cylindrical configurations. Again, the measured values and those calculated (MCNP-4b2) were in good agreement.

A comprehensive validation section in this study is not needed because the purpose of this study is to determine criticality credibility and investigate the various parameters present in the SDA and how they affect reactivity. However, any bias associated with these calculations will not affect the conclusion that criticality is not credible in the SDA.

4. EVALUATION AND RESULTS

The exact condition and distribution of the fissile material in the waste is unknown. The waste material in the SDA is certainly not an ordered configuration. In most cases, the drums or boxes were placed into the pits and trenches by large-scale dumping methods. In some cases, once dumped into the burial area, the drums were driven over by a large bulldozer/tractor to compact the waste. Certainly degradation of the waste has occurred, as has subsidence. Both would result in soil mixing with the waste.

For criticality to occur in the SDA, several unlikely concurrent parameters must exist. There must be sufficient fissile mass; the fissile mass must be at or near the optimum concentration; the fissile mass must be in or nearly in an optimal geometry; there must be optimal or near optimal moderation (criticality in the SDA is not possible without moderation; the fissile masses required for an unmoderated criticality are in the tens of kilograms and are not credible); near-optimal reflection; and the fissile mass must be in a waste matrix that lacks diluent and neutron absorber, which are known to exist in most waste matrices.

The fissile material buried in the SDA is associated with the waste stored there and as such, is mixed with various materials (rags, paper, sludge, metal and glass) that act as mild neutron absorbers or dilute the system, taking up space and reducing the fissile concentration. Some waste forms provide more diluent than others, e.g., sludges and grouts versus HEPA filter media. Although it is very unlikely, the potential for a waste package to contain an unsafe mass does exist. However, packages with even kilogram quantities of fissile material would be extremely difficult to achieve criticality and all scenarios require near optimum moderation (water). The fissile material must first exist and must be spread throughout a near spherical geometry. As little as 520 g of plutonium can be made critical in a sphere containing plutonium and water and would easily fit inside a 55-gallon drum. A system such as this would also require near optimum water moderation and reflection and a homogeneous distribution of plutonium in solution at about 30 g per liter. Plutonium and/or uranium in the SDA is most likely in an oxide form, which is insoluble in water. Therefore unsafe plutonium solutions are not possible. Deviations from the ideal conditions described above will generally increase the critical mass and reduce the reactivity of the system. In short, achieving criticality with the fissile masses expected in the waste forms is not credible even with the introduction of moderator.

An evaluation for potential criticality in the SDA must address the parameters that affect reactivity of the waste. These parameters include the amount of fissile mass and moderator present, geometrical configurations, the presence of diluents or neutron absorbers, reflection conditions surrounding the fissile systems, and the concentration or distribution of the fissile material in the waste. Most of these parameters would have to be optimized in some combination to achieve a critical system. As deviations from optimum conditions occur, the reactivity of the systems decreases dramatically.

Calculations were performed to determine k_{eff}s for in most cases, unrealistic postulated configurations with the three waste types of concern. Although unrealistic, these calculations are useful to demonstrate the effects of the parameters described above and the reactivity effects between conservative models and the expected actual realistic configurations in the waste buried in the SDA. Calculations incorporating idealized conservatisms into the modeled systems will obviously result in very reactive k_{eff}s. These models are generally very ordered and represent configurations that would not be expected in actual waste forms. Calculations presented here do not represent the reactivity of the buried waste, but show that as the systems deviate from these ordered systems, reactivity readily decreases.

4.1 High-Efficiency Particulate Air Filters

4.1.1 Filter Arrays in Soil

Variously sized HEPA filters were used at a number of facilities in support of several operational lines at the RFP. The HEPA filters of concern came from the pre-1970 timeframe. These HEPA filters, also known as chemical warfare service filters, were constructed of either a wood or steel frame with a cellulose (i.e., paper) filter media. The filter media were impregnated with asbestos for fire retardation purposes. In the 1970s, the cellulose filter media was replaced by a glass-type filter media. A review of historical data indicates that no drums containing this glass-type filter media have been buried in the SDA; therefore, this study was restricted to the cellulose type of HEPA filter.[c]

The specifications for HEPA filters for the pre-1970 timeframe are delineated in military specifications MIL-F-51068C (Military Specification 1970a), MIL-F-51079A (Military Specification 1970b), and MIL-F-51079C (Military Specification 1980). The filter dimension specifications are listed in Table 1.

Table 1. Dimensions of high-efficiency particulate air filters.

	Dimensions (in.)		
Filter Type	x	y	z
1	8 (+0, -1/16)	8 (+0, -1/16)	3 1/16 (+1/16, -0)
2	8 (+0, -1/16)	8 (+0, -1/16)	5-7/8 (+1/16, -0)
3	12 (+0, -1/16)	12 (+0, -1/16)	5-7/8 (+1/16, -0)
4	24 (+0, -1/8)	24 (+0, -1/8)	5-7/8 (+1/16, -0)
5	24 (+0, -1/8)	24 (+0, -1/8)	11 ½ (+1/16, -0)
6	24 (+0, -1/8)	24 (+0, -1/8)	11 ½ (+1/16, -0)

The smaller filters (Types 2 and 3) were used as the pre-filters or first- and second- stage filters at RFP. The larger filters (Types 4, 5, and 6) were used as the plenum filters and received much less fissile material accumulation. Very few Type 1 filters were used. The filter media were housed in a plywood frame 1.9-cm (3/4-in.) thick with aluminum separator plates in the filter itself. The filtering medium was constructed as a single continuous sheet that was wound around a series of 0.48-cm (3/16-in.) mandrels. The filter media specifications included a minimum thickness of 0.038 cm (0.015 in.) with a maximum thickness of 0.0102 cm (0.040 in.). Schematics of the filter are shown in Figures 4 and 5 (LMITCO 1998).

c. Paul J. Sentieri, personal conversation with Bruce H. Becker, May 2000, Idaho National Engineering and Environmental Laboratory, Bechtel BWXT Idaho, LLC.

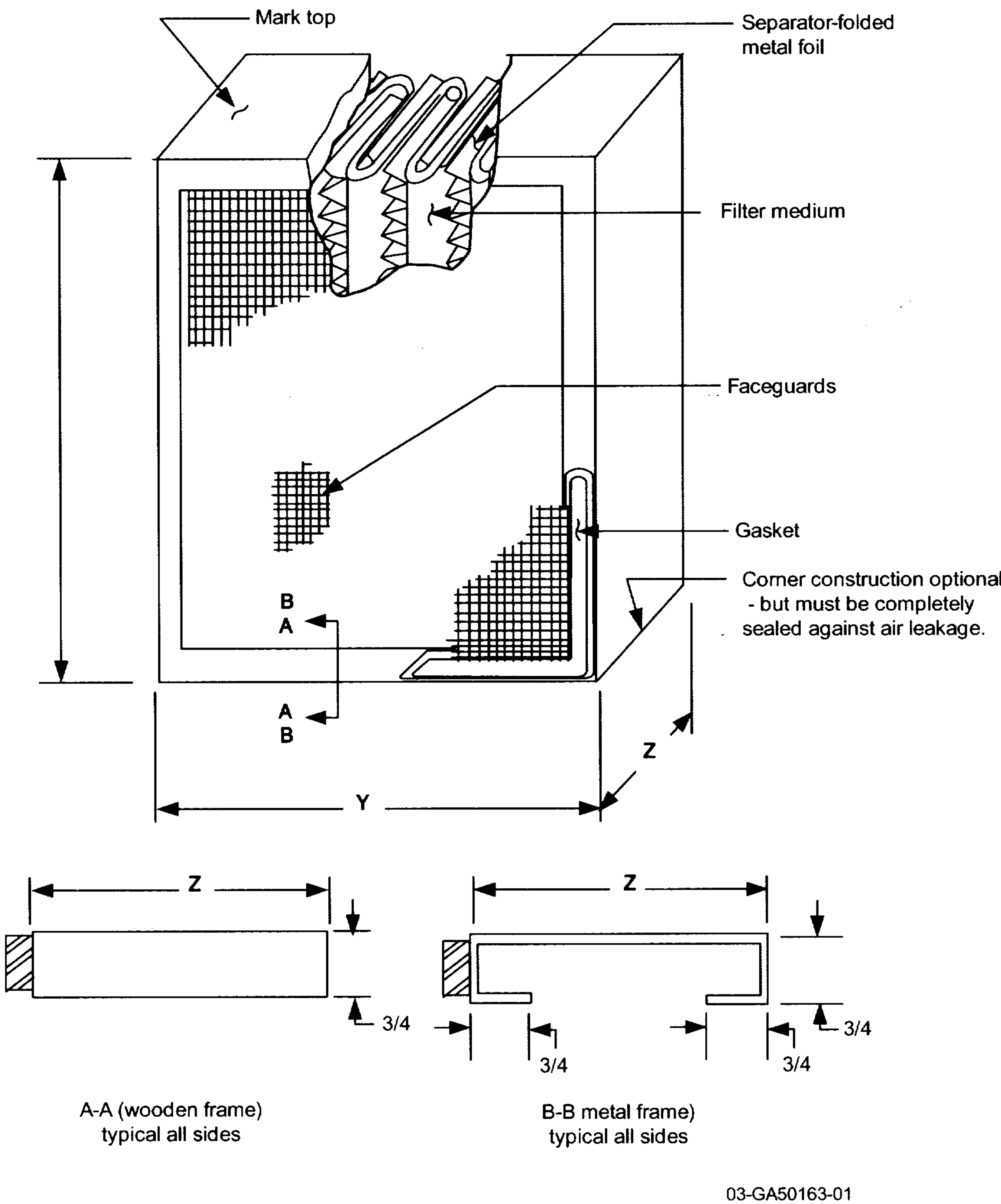

Figure 4. Sketch of a high-efficiency particulate air filter (Military Specification 1970a).

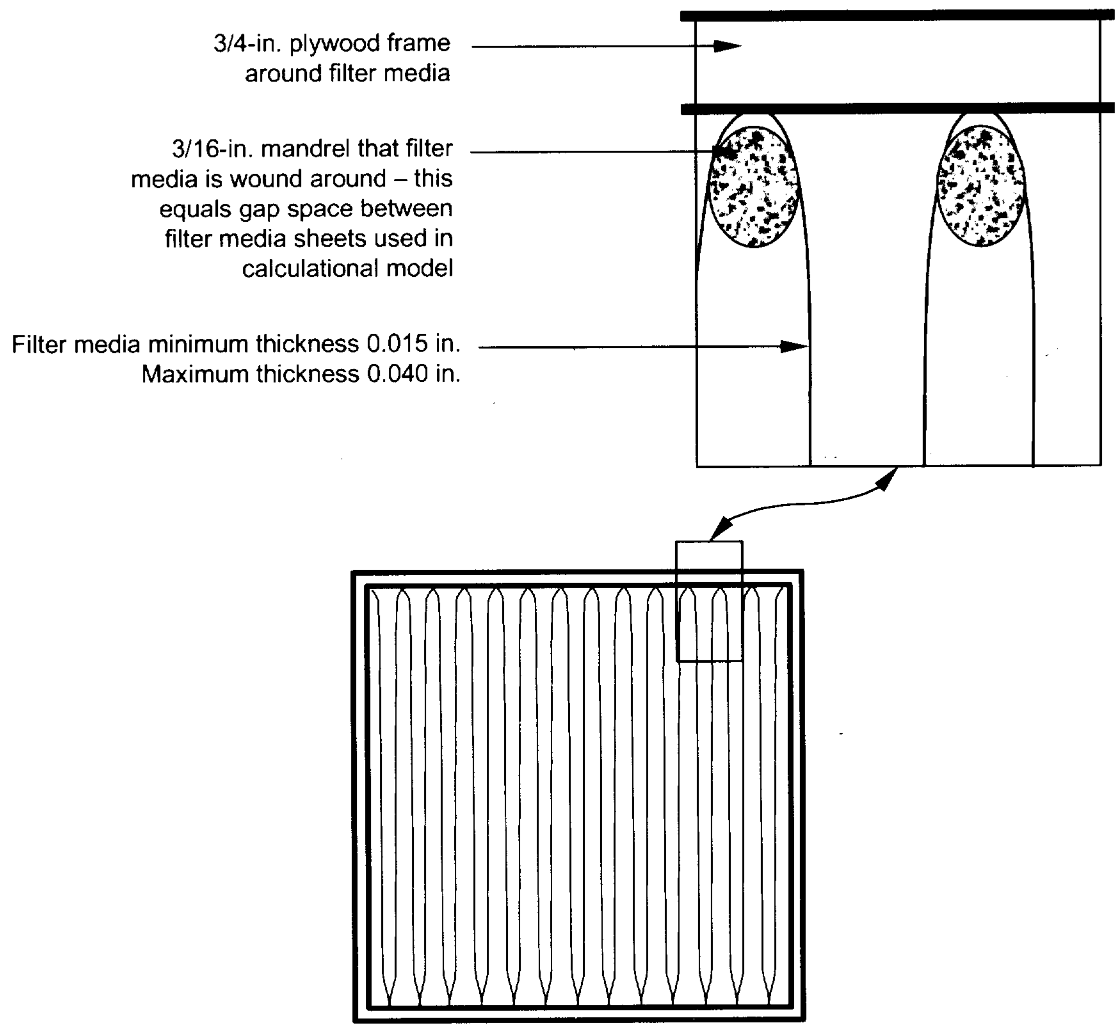

Figure 5. Schematic of the high-efficiency particulate air filter configuration.

For this study, the aluminum spacers were ignored in the filter models. Aluminum has a low neutron absorption cross-section and would have a negligible effect on reactivity. The presence of the aluminum spacers helped the filters maintain structural integrity along with the wood frames; however, they would also take up space and preclude water, thus making it conservative to leave them out of the calculational model.

Past retrieval efforts have occurred in the SDA (Thompson 1972). A retrieval effort was undertaken in the early 1970s and documented in an attempt to quantify plutonium migration in pits in the SDA and determine the condition of waste storage containers including drums, cardboard boxes, and wooden boxes. At the time of this retrieval effort, which took place more than 30 years ago, the waste had been emplaced for approximately 15 years. During the retrieval effort, Thompson (1972) noted that some of the waste drums were in excellent condition while others had corroded through. Thompson also stated that it was apparent that damage to the barrels during the dumping operations was extensive and had resulted in many open barrels. Plywood boxes and cardboard cartons were deteriorated to the extent that they had no containment value. Thompson also documented the results of samples taken in the waste matrix to determine plutonium migration: very limited, if any, migration of the plutonium had occurred. These data support the conclusion that the waste matrix material is probably intermixed with soil in a disordered configuration, most likely in the case of the cardboard cartons and wooden boxes. In addition, the HEPA filters were constructed of cellulose material similar to the cardboard cartons that had deteriorated. This similar construction supports the argument that the filter media and wooden frames likely also have deteriorated.

The filters evaluated here were for most cases, conservatively assumed to be intact and were modeled as such to evaluate the upper-bound reactivity that could be achieved in an ordered array with the plutonium dispersed in a homogeneous manner among the filters, which is extremely conservative.

In the first series of cases, an array of filters in soil was considered. Past RFP practices for shipping included shipping HEPA filters in cardboard boxes. No conclusive data can be found to indicate that only the large, lower-loaded HEPA filters were shipped in this fashion. Therefore, for this study, an array of highly loaded first- and second-stage filters was assumed to have been shipped in cardboard containers, placed together in the pit and have degraded. Therefore, the filters were modeled in various arrangements in soil. In addition, early placement of the waste into the SDA was done in an orderly fashion to preserve space. In the case of square boxes, drums, and large wooden boxes, an orderly stack was assembled in the waste array. However, high radiation exposures to workers led to the abandonment of this practice in the late 1960s. Once again, no conclusive, readily available data exist to refute that these filters were not placed into the SDA in a stacked orderly fashion. A good argument can be made that the ordered array is now a compressed disordered soil infiltrated array because of material degradation of the filters and the weight of the overburden. The compressed and disordered soil infiltrated array would be much less reactive than that which is modeled.

A set of comparison cases was modeled to determine which of the first- and second-stage filters, the Type 2, 20.3 × 20.3 × 15-cm (8 × 8 × 5-7/8-in.) HEPA filter (see Table 2), or the Type 3, 30.5 × 30.5 × 15-cm (12 × 12 × 5-7/8-in.) filter (see Table 3) provides an enveloping case. The base model consisted of 200 g of plutonium (95% Pu-239 and 5% Pu-240) in the form of PuO_2. The value of 200 g was obtained from estimates of the high loading that could be possible in the first- and second-stage smaller filters (see footnote b).

Table 2. 2 × 1 × 2 array of Type 2 - 20.3 × 20.3 × 15-cm (8 × 8 × 5-7/8-in.) glovebox high-efficiency particulate air filters to determine density effects.[a]

Case Name	Thin Layer of Material on Filter Media (g/cm^3)	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
8 × 8 × 5_13a	2	0.9510 ± 0.0010	0.953
8 × 8 × 5_13b	3	0.9480 ± 0.0012	0.950
8 × 8 × 5_13c	4	0.9478 ± 0.0011	0.950
8 × 8 × 5_13d	5	0.9497 ± 0.0011	0.952
8 × 8 × 5_13e	6	0.9491 ± 0.0010	0.951
8 × 8 × 5_13f	7	0.9483 ± 0.0011	0.950
8 × 8 × 5_13g	8	0.9502 ± 0.0010	0.952
8 × 8 × 5_13h	9	0.9484 ± 0.0011	0.951
8 × 8 × 5_13i	10	0.9460 ± 0.0011	0.948
8 × 8 × 5_13j	11	0.9496 ± 0.0010	0.952
8 × 8 × 5_13k	11.46	0.9479 ± 0.0011	0.950

a. The array has 1.0-cm (0.4-in.) edge-to-edge spacing between filters with 200 g of plutonium per filter and saturated soil as the reflector with 100% water-flooded high-efficiency particulate air filters containing a varied density of plutonium dioxide.

The PuO_2 was assumed to be evenly distributed throughout each filter as a layer on one side of each of the sheets of filter cellulose media. Assuming 200 g in each filter with optimal moderation is very conservative. The density of the PuO_2 was varied from a theoretical density of 11.46 g/cm^3 to a model density of 2 g/cm^3. As the density decreased, the corresponding thickness of the PuO_2-containing layer and the void fraction in the PuO_2 increased. The gap between each of the filter media sheets, along with any corresponding void fraction in the PuO_2 layer on the filter media, was flooded with water in these cases. The filters in these comparison cases were placed at a 1-cm (0.4-in.) edge-to-edge spacing. The space between the filters was filled with water-saturated soil. The 1-cm (0.4-in.) edge-to-edge spacing was chosen in an attempt to inject a limited amount of realism into the base model. The placement of the filters into the SDA could have been in an orderly fashion, but the covering of the cardboard boxes with the overburden and subsequent degradation would have led to some disruption of an orderly array of stacked cardboard boxes.

The results of these comparison cases are found in Tables 2 and 3. An illustration of the filter used in the calculational model is provided in Figure 6. An illustration of the array of filters, as modeled in the calculation, is shown in Figure 7. A case comparison was conducted to determine the more reactive configuration between a 2 × 2 × 1 array and a 2 × 1 × 2 array of the Type 2 filters containing PuO_2 at a density of 2 g/cm^3. The 2 × 1 × 2 array yielded a calculated $k_{eff} + 2\sigma = 0.953$ while the 2 × 2 × 1 array yielded a calculated $k_{eff} + 2\sigma = 0.894$. From the results of the calculations, a 2 × 1 × 2 array of filters was more reactive and was chosen as the base model.

Table 3. 2 × 1 × 2 array of Type 3 - 30.5 × 30.5 × 15-cm (12 × 12 × 5-7/8-in.) glovebox high-efficiency particulate air filters to determine density effects.[a]

Case Name	Thin Layer of Material on Filter Media (g/cm^3)	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
12 × 12 × 6_2a	2	0.8992 ± 0.0008	0.901
12 × 12 × 6_2b	3	0.9010 ± 0.0009	0.903
12 × 12 × 6_2c	4	0.8980 ± 0.0008	0.900
12 × 12 × 6_2d	5	0.8979 ± 0.0009	0.900
12 × 12 × 6_2e	6	0.8995 ± 0.0007	0.901
12 × 12 × 6_2f	7	0.9008 ± 0.0008	0.902
12 × 12 × 6_2g	8	0.8989 ± 0.0009	0.901
12 × 12 × 6_2h	9	0.9006 ± 0.0008	0.902
12 × 12 × 6_2i	10	0.8994 ± 0.0008	0.901
12 × 12 × 6_2j	11	0.9009 ± 0.0008	0.902
12 × 12 × 6_2k	11.46	0.8997 ± 0.0009	0.902

a. The array has 1.0-cm (0.4-in.) edge-to-edge spacing between filters with 200 g of plutonium per filter with saturated soil as the reflector and 100% water-flooded high-efficiency particulate air filters containing a varied density of plutonium dioxide.

Table 4. Edge-to-edge spacing varied in 2 × 1 × 2 array of Type 2 glovebox high-efficiency particulate air filters.[a]

Case Name	Edge-to-Edge Distance Between Filters in Soil (cm)	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
8 × 8 × 5_10	0	0.9741 ± 0.0011	0.976
8 × 8 × 5_10a	1	0.9510 ± 0.0010	0.953
8 × 8 × 5_10b	2	0.9257 ± 0.0012	0.928
8 × 8 × 5_10c	3	0.9052 ± 0.0010	0.907
8 × 8 × 5_10d	4	0.8827 ± 0.0010	0.885
8 × 8 × 5_10e	5	0.8614 ± 0.0011	0.863
8 × 8 × 5_10f	10	0.7875 ± 0.0010	0.790
8 × 8 × 5_10g	20	0.7322 ± 0.0010	0.734

a. The array has 200 g of plutonium per filter and saturated soil as the reflector with 100% water-flooded high-efficiency particulate air filters.

These comparison cases in Tables 2 and 3 show that the distribution of 200 g of plutonium in the form of PuO_2 in the smaller filter is more reactive than the same distribution in the larger filter. In addition, the reactivity of the system is relatively insensitive to the density used for the PuO_2 layer on the filter media. Therefore, the gram density used for the PuO_2 layers in the remainder of the cases was 2 g/cm^3, which is a more likely density of PuO_2 to get airborne and into the HEPA filters.

Two more comparison cases were evaluated to determine that the initial model was enveloping for the remaining models to be developed. In the first comparison case, the 2 × 1 × 2 array of Type 2 filters with the 1-cm (0.4-in.) edge-to-edge spacing, as described earlier in this section, was evaluated with a different mandrel. In this model, the mandrel present in the filter was modeled as 0.16 cm (1/16 in.). The data conflicted between superseded versions of the military specifications (Military Specification 1970b [MIL-F-51079A] and 1980) about whether a 0.16-cm (1/16-in.) mandrel met the specification. To address this question, a single comparison case was evaluated. By reducing the size of the mandrel by one-third, the number of media sheets present in the filter increased three-fold while the gap spacing between sheets decreased. However, the total void in the filter was reduced only slightly because of the very thin thickness of the filter media sheets. The results from the 2 × 1 × 2-array case yielded a calculated $k_{eff} + 2\sigma = 0.959$. This k_{eff} is statistically equivalent to the calculated k_{eff} for Case 8 × 8 × 5_10a (see Table 4) that was shown to be 0.953. Therefore, the size of the mandrel, either 0.48 cm (3/16 in.) or 0.16 cm (1/16 in.), is not relevant to the reactivity of the model.

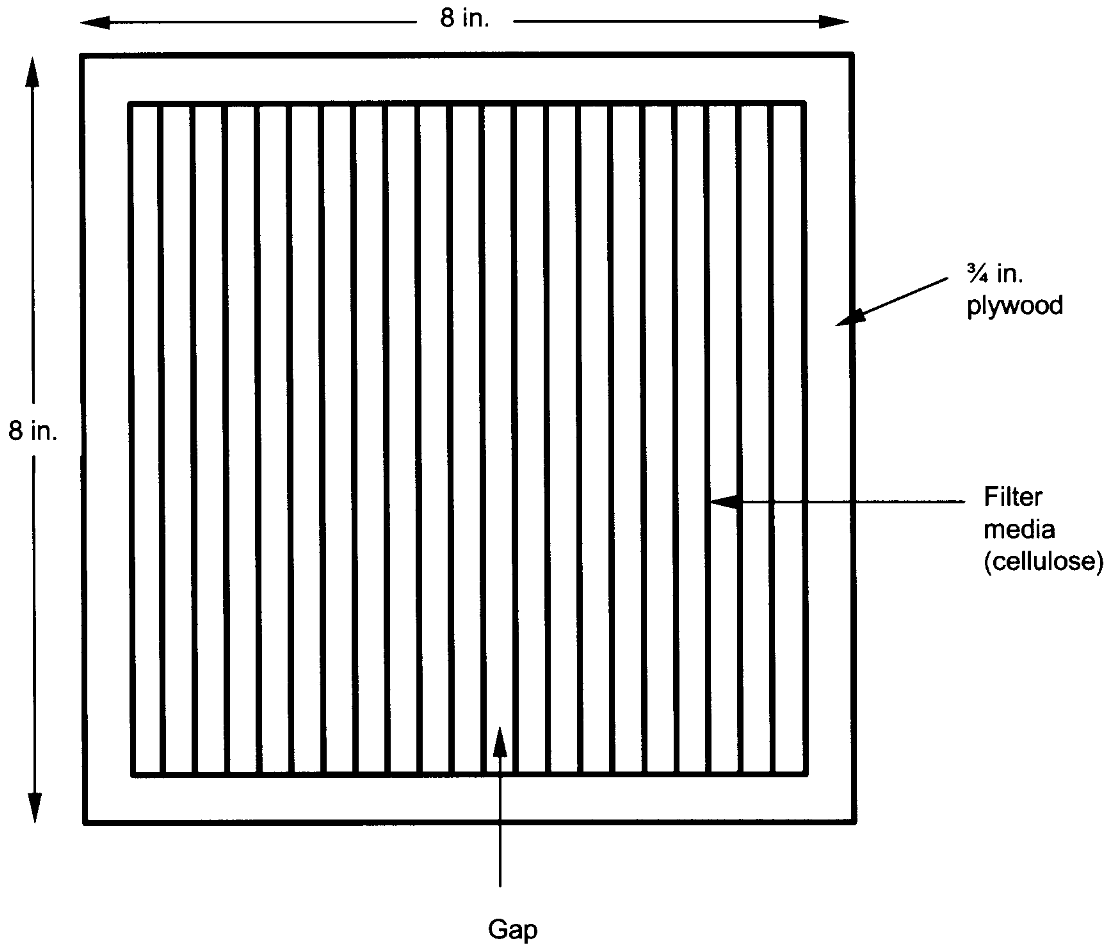

Figure 6. Planar view (x-y) of a filter as modeled for calculation purposes.

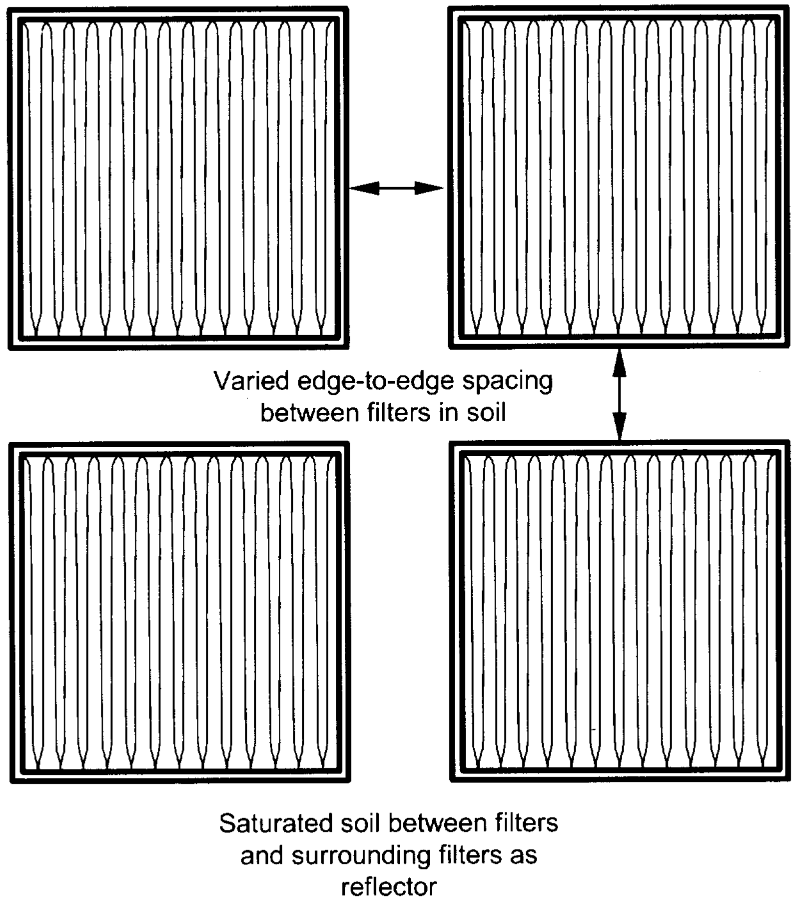

Figure 7. Planar view (x-y) of spacing of filters in soil.

In the second comparison case, the filter media sheet was evaluated at maximum thickness. The Military Specification (1980) appropriate to filter media allowed for a minimum filter thickness of 0.038 cm (0.015 in.) and a maximum thickness of 0.102 cm (0.040 in.). Once again, the same configuration of filters in the 2 × 1 × 2 array was considered with a maximum filter media thickness of 0.102 cm (0.040 in.). The calculated $k_{eff} + 2\sigma$ for this case was given as 0.949. This k_{eff} is statistically equivalent to the calculated k_{eff} for case 8 × 8 × 5_10a, which was shown to be 0.953 (see Table 4). Therefore, the thickness of the filter media sheets, 0.038 cm (0.015 in.) or 0.102 cm (0.040 in.), is not relevant to the reactivity of the model.

The base model used for the remaining cases was chosen to be the filter with the 0.48-cm (3/16-in.) mandrel and the filter media sheets with a thickness of 0.038 cm (0.015 in.). Applying this model, a parametric study was completed to determine the reactivity effect of spacing between filters in the soil, since degraded waste will either be compressed and/or separated. For this set of calculations, a 2 × 1 × 2 array of Type 2 filters was used. The edge-to-edge spacing between filters was varied from 0 to 20 cm (0 to 7.9 in.), as incremented in Table 4, to evaluate the reactivity effect of soil between filters. The results of these cases are given in Table 4. The soil between the filters was modeled as fully saturated (the 40% available void fraction in the soil was filled with water). This is a valid modeling assumption because if full flooding occurs in the filters themselves, then the surrounding soil also must be fully flooded. These calculations show that as expected, if the filters are separated by soil, the calculated k_{eff} significantly decreases. Again, the 2 × 1 × 2 array model is a very orderly array of four highly loaded filters in close proximity.

A 3 × 3 × 3 array of Type 2 filters containing no water in a dry-soil environment was also evaluated. The filters were separated by 1 cm (0.4 in.) of soil with a 200-g Pu-239 fissile loading per filter. The calculated $k_{eff} + 2\sigma$ for the 3 × 3 × 3 array (27 filters with a total of 5.4 kg Pu-239) model was equal to 0.827. It should be emphasized that these are highly ordered arrays of highly loaded filters, which are not expected in the SDA. This study shows that as realistic assumptions are introduced into the calculational models, the reactivity of the systems decreases dramatically.

A more-expected nominal loading per filter would be in the range of 10 to 50 g of plutonium per filter (Clements 1982). A set of cases was evaluated to determine how many filters would be necessary to create a critical configuration if the loading per filter was reduced from 200 g of plutonium per filter to 50 g. The results of these cases are given in Table 5.

As shown in Table 5, when optimized models for filters that contain more realistic loadings are placed together in an array, a large number of filters can be assembled and the system still remains subcritical. This effect is very important because most of the filters are expected to actually contain fissile loading in the range of 30.0 g plutonium per filter.[d]

Table 5. Expected fissile-loadings for Type 2 filters modeled in variously sized arrays.[a]

Case Name	Size of Array	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma\sigma$
8 × 8 × 5_14a	2 × 2 × 2	0.6635 ± 0.0008	0.665
8 × 8 × 5_14b	3 × 3 × 3	0.7773 ± 0.0007	0.779
8 × 8 × 5_14c	4 × 4 × 4	0.8352 ± 0.0006	0.836
8 × 8 × 5_14d	5 × 5 × 5	0.8704 ± 0.0006	0.872
8 × 8 × 5_14e	6 × 6 × 6	0.8907 ± 0.0006	0.892

a. These arrays have 1.0-cm (0.4-in.) edge-to-edge saturated soil spacing between filters with 50 g of plutonium per filter with saturated soil as reflector and 100% water-flooded high-efficiency particulate filters.

In the next set of cases, the effects of soil and water were evaluated as moderating materials in the gaps of the filters. It is expected (because of subsidence in the pit and degradation of containers and filters) that any water-moderating material introduced to the filters would be muddy in nature (a combination of soil and water). Water intrusion would lead to a combination of soil and water being intermixed in the filter media. Degradation of the filters and pit subsidence during the burial period would intermix soil in the filter itself or result in crushed filter media that cannot be optimally moderated. The previous cases were evaluated with full-density water filling the gaps between the PuO_2-laden filter media sheets. For this series of cases, a 2 × 2 × 3 array of Type 2 filters (containing 200 g of plutonium per filter) was modeled with a combination of water and soil filling the void in the filter gaps.

d. Almodovar, Sixto T., Enercon Innovative Solutions, Memorandum to Paul J. Sentieri, Idaho National Engineering and Environmental Laboratory, July 20, 2001, "Completion of task 3.1 of contract K00-564419-003, revision date of 05/08/01, Historical data on Rocky Flats Flanders Filter."

The filters were modeled with an edge-to-edge soil spacing of 1 cm (0.4 in.). The first series of cases in this set consisted of the filter gap spacing being filled with SDA soil. The SDA soil has a void fraction of 40%. Cases were evaluated that consisted of varied amounts of water filling this 40% void fraction. The amount of water present in the void fraction varied from 0 to 100%. The results from these cases are given in Table 6.

One single case was evaluated that consisted of a 2 × 2 × 3 array of filters (Case 8 × 8 × 5_15f) that was similar to Case 8 × 8 × 5_15e. In Case 8 × 8 × 5_15f, the soil, acting as the reflector around the system and the soil interspersed between the filters, was modeled containing no water. The calculated $k_{eff} + 2\sigma$ for Case 8× 8 × 5_15f was shown to be equal to 0.690. Again, this demonstrates the dependence of flooding in the system to achieve higher k_{eff}s. In addition, it should be noted that this set of cases was used to evaluate a 2 × 2 × 3 array of filters. The increased array size emphasizes the dependence of reactivity on the water content or degree of saturation of the moderating material intermixed with the fissile material. As soil is introduced into the filters, the reactivity of the system decreases dramatically, requiring more highly loaded filters to assemble a reactive configuration.

Table 6. 2 × 2 × 3 array of Type 2 filters with varied fraction of water volume in soil modeled interstitial to the filter media.[a]

Case Name	Fraction of Water in 40% Void Fraction in Soil in Filter (%)	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
8 × 8 × 5_15a	100	0.9779 ± 0.0010	0.980
8 × 8 × 5_15b	75	0.9342 ± 0.0011	0.936
8 × 8 × 5_15c	50	0.8821 ± 0.0011	0.884
8 × 8 × 5_15d	25	0.7906 ± 0.0010	0.793
8 × 8 × 5_15e	0	0.7612 ± 0.0012	0.764

a. The array has 1.0-cm (0.4-in.) edge-to-edge saturated soil spacing between filters with 200 g of plutonium per filter with saturated SDA soil as the reflector (40% water volume fraction) and water-flooded high-efficiency particulate air filters.

As shown by these results, the reactivity of the system is very dependent on the amount of water present in the filters. The next series of cases is similar to the previous set. In this set, however, the gap space between the filter media sheets is filled with a combination of soil and water at various ratios. The results of this series of cases are given in Table 7, and show the negative effect soil has on the reactivity of the system.

Table 7. Varied mixture of water and soil modeled interstitially in Type 2 filters stacked in $2 \times 1 \times 2$ array.[a]

Case Name	Volume Fraction of Water in Filter Gap Region (%)	Volume Fraction of Soil in Filter Gap Region (%)	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
8 × 8 × 5_13a	100	0	0.9510 ± 0.0010	0.953
8 × 8 × 5_16a	90	10	0.9249 ± 0.0010	0.927
8 × 8 × 5_16b	80	20	0.8948 ± 0.0011	0.897
8 × 8 × 5_16c	70	30	0.8639 ± 0.0010	0.866
8 × 8 × 5_16d	60	40	0.8291 ± 0.0011	0.831
8 × 8 × 5_16e	50	50	0.7909 ± 0.0012	0.793

a. The array has 1.0-cm (0.4-in.) edge-to-edge spacing between filters with 200 g of plutonium per filter flooded with a mixture of water and soil with saturated soil as the reflector.

These results show that as soil displaces water in the filters, the calculated k_{eff} for the system decreases, which in turn indicates the effect of water moderation on the system.

The soil composition in the SDA contains a certain amount of B-10 in the form of B_2O_3 that was ignored in previous cases. The nominal amount of B_2O_3 is approximately 0.05 wt% of the soil composition (Callow et al. 1991). In natural boron, the isotopic composition is approximately 20% B-10 and 80% B-11. The boron isotope B-10 has a high thermal-neutron-absorption cross-section. A set of cases was evaluated to determine the effect boron would have if included in the system. This set evaluated the $2 \times 1 \times 2$ water-moderated array of Type 2 filters with an edge-to-edge soil spacing of 1.0 cm (0.4 in.) in water-saturated soil. The filters were loaded at 200 g of plutonium in the form of PuO_2, as previously described. Boron was included in the water in the gaps between the plutonium-laden filter media. In all of the previous cases, the boron was modeled as completely comprising B-11. In this case, boron was modeled as comprising B-10 and B-11. The amount of B-10 was varied from 100% of an assumed 19% isotopic to 25% of the 19% isotopically present. The results of these cases are given in Table 8.

As shown in Table 8, the case in which a $2 \times 1 \times 2$ array was modeled with no B-10 yielded a $k_{eff} + 2\sigma$ of 0.953 (Case 8 × 8 × 5_10a). A comparison to this calculated k_{eff} shows the Δk difference when various amounts of B-10 from the soil are included. These results show that the boron absorber present has little effect on the reactivity of the system.

Subsidence has occurred on a regular basis at the SDA and subsidence is evidence of compaction of the waste. A set of cases was evaluated to consider these subsidence events. These cases determined the effect on reactivity if the gap spacing in the filter was reduced so that the cross-sectional area of the filter is decreased with the height and length of the filters being preserved. This decrease effectively excludes water from in the filter as the filter is compressed in the horizontal direction. This exclusion of water decreases the amount of moderator present, thus decreasing the ratio of hydrogen to plutonium. The gap spacing in the Type 2 filter was decreased uniformly over the cross section of the filter. Each gap was reduced to approximately 75, 50, and 25% of its original width. The results from these cases are given in Table 9.

Table 8. Varied mixture of water and boron modeled interstitially in 2 × 1 × 2 array of Type 2 glovebox high-efficiency particulate air filters.[a]

Case Name	Weight Fraction of B-10 from Soil in Water in Filter	Total B-10 Present in the Soil (%)	Solids Parts per Million (mg/kg)	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
8 × 8 × 5_10a	0	0	0	0.9505 ± 0.0010	0.953
8 × 8 × 5_17a	3.5×10^{-5}	100	44	0.9064 ± 0.0011	0.909
8 × 8 × 5_17b	2.625×10^{-5}	75	32.8	0.9172 ± 0.0010	0.919
8 × 8 × 5_17c	1.75×10^{-5}	50	21.9	0.9287 ± 0.0010	0.931
8 × 8 × 5_17d	8.75×10^{-6}	25	10.9	0.9381 ± 0.0010	0.940

a. The array has 1.0-cm (0.4-in.) edge-to-edge saturated soil spacing between filters with 200 g of plutonium per filter flooded with water containing B-10 with saturated soil as the reflector.

The results given in Table 9 show that as the filter is compressed, the reactivity decreases. Therefore, any compression of the filter will decrease the reactivity of the system or, in the case of up to approximately 75% compaction, it remains the same (in statistical uncertainty). These results show the effects of geometry and water moderation on the reactivity of the system and that compaction reduces reactivity.

Table 9. Compressed Type 2 filters flooded with water in a 2 × 1 × 2 array.[a]

Case Name	Gap Thickness of Original (%)	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
8 × 8 × 5_10a	100	0.9510 ± 0.0010	0.953
8 × 8 × 5_18a	74.5	0.9504 ± 0.0009	0.952
8 × 8 × 5_18b	48.6	0.9196 ± 0.0011	0.922
8 × 8 × 5_18c	22.75	0.8432 ± 0.0011	0.845

a. The array has 1.0-cm (0.4-in.) edge-to-edge saturated soil spacing between filters with 200 g of plutonium per filter with saturated soil as the reflector and 100% water-flooded filters compressed to reduce the gap spacing in filters.

In all of the previous filter cases, PuO_2 was dispersed evenly throughout the filter as a thin layer on each of the filter media sheets. A set of cases was used to evaluate the reactivity effects of consolidating the oxide over a smaller area of each media sheet, which would be expected. This effect essentially increases the thickness of the oxide layer per sheet in the area that contains PuO_2 (assuming the total mass of PuO_2 in the filter is preserved). A schematic example of the calculational model used is given in Figure 8.

In the form of PuO_2, 200 g of plutonium were spread over an area of 75, 50, 25, and 10% of the total filter surface area. A 2 × 1 × 2 array of Type 2 filters was modeled in saturated soil. The filters were modeled with a 1-cm (0.4-in.) edge-to-edge spacing in the soil. As the area decreases over which the oxide is spread, the thickness of the oxide layer per sheet increases, as mentioned above. The layers of oxide were modeled so that interaction between the filters was maximized. In a single layer of the 2 × 1 × 2 array, the oxide layers were modeled over the entire filter media sheets in the "x" direction and shifted in the "y" direction. The oxide was spread over the entire axial region of each filter. A schematic example of the configuration modeled is shown in Figure 9. The results from these cases are given in Table 10.

Table 10. Reduction in areal dispersion of plutonium dioxide on filter media in a 2 × 1 × 2 array of Type 2 glovebox high-efficiency particulate air filters.[a]

Case Name	Filter Media Sheet Area of Modeled Oxide Layer (%)	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
8 × 8 × 5_10a	100	0.9510 ± 0.0010	0.953
8 × 8 × 5_20a	75	0.9086 ± 0.0010	0.911
8 × 8 × 5_20b	50	0.8285 ± 0.0011	0.831
8 × 8 × 5_20c	25	0.6897 ± 0.0011	0.692
8 × 8 × 5_20d	10	0.5623 ± 0.0011	0.564

a. The array has 1.0-cm (0.4-in.) edge-to-edge saturated soil spacing between filters with 200 g of plutonium per filter with saturated soil as the reflector and 100% water-flooded high-efficiency particulate air filters so that oxide is dispersed and reduced in the filters.

As the area decreases over which the 200 g of plutonium is dispersed, the calculated k_{eff} decreases, as shown in Table 10. Even though the fissile loading is preserved, the cross-sectional area of interaction between the layers of PuO_2 on adjacent filter media sheets decreases. This is a good indication of the dependence of the homogeneity on the reactivity of the system. As the plutonium in the system becomes less homogeneously distributed in the filters, which would be expected, the reactivity greatly decreases. This relates to the geometrical distribution of fissile material, moderation, and the neutron leakage properties of the various configurations.

The next postulated configuration that was evaluated relative to the glovebox HEPA filters consisted of a single overloaded filter that was water flooded and reflected by fully saturated soil. For this set of cases, a Type 3, 30.5 × 30.5 × 15.2-cm (12 × 12 × 6-in.) filter was modeled. The larger volume of this filter as compared with the Type 2 filter will allow these larger fissile masses to be spread out over a larger volume and achieve more optimal moderation. As more fissile material is distributed throughout the filter, more moderating material is excluded, thus exhibiting a tradeoff between mass of fissile material and moderator present. The results from this set of cases are given in Table 11.

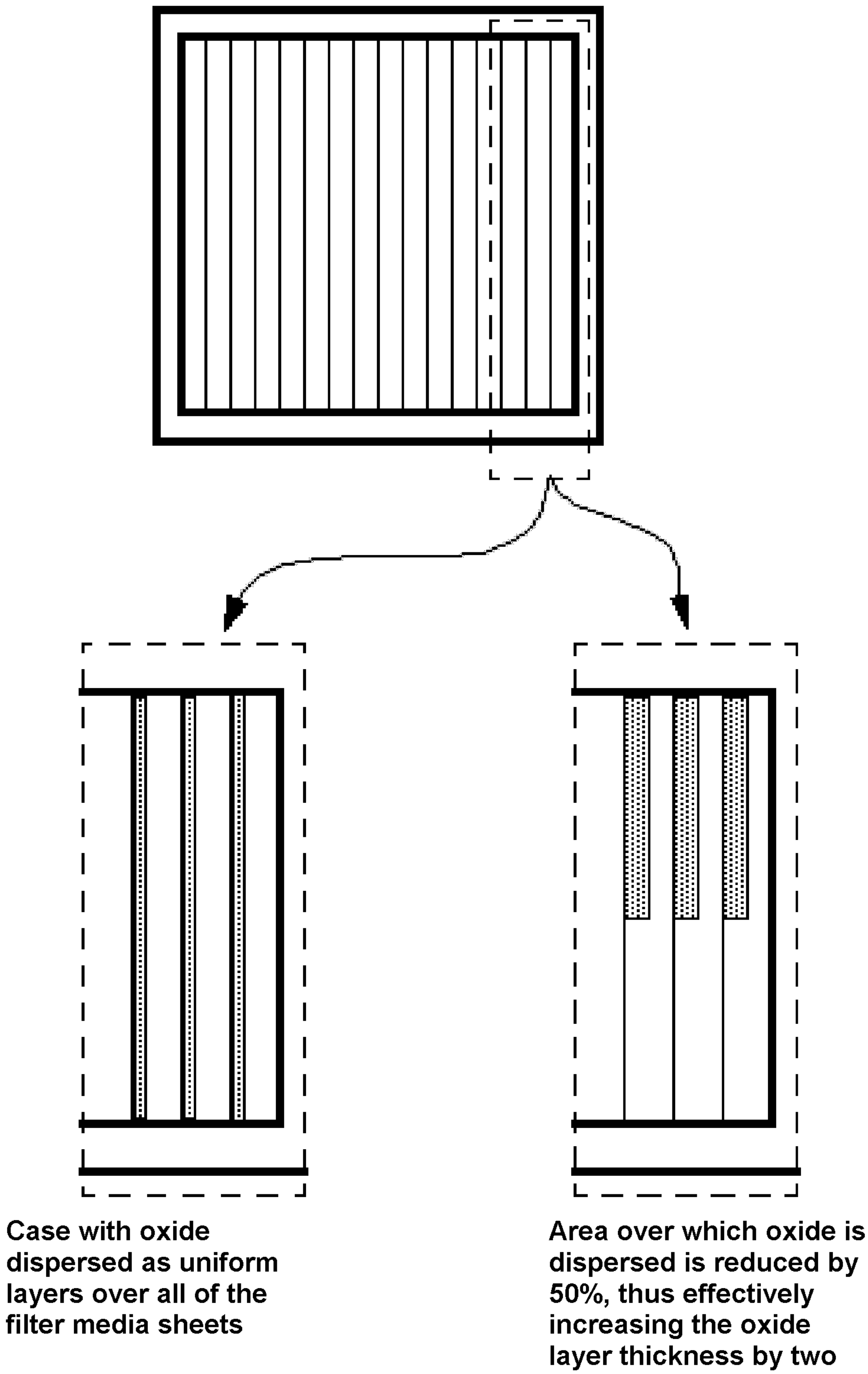

Figure 8. Example of plutonium dioxide dispersed over reduced area of filter media sheets.

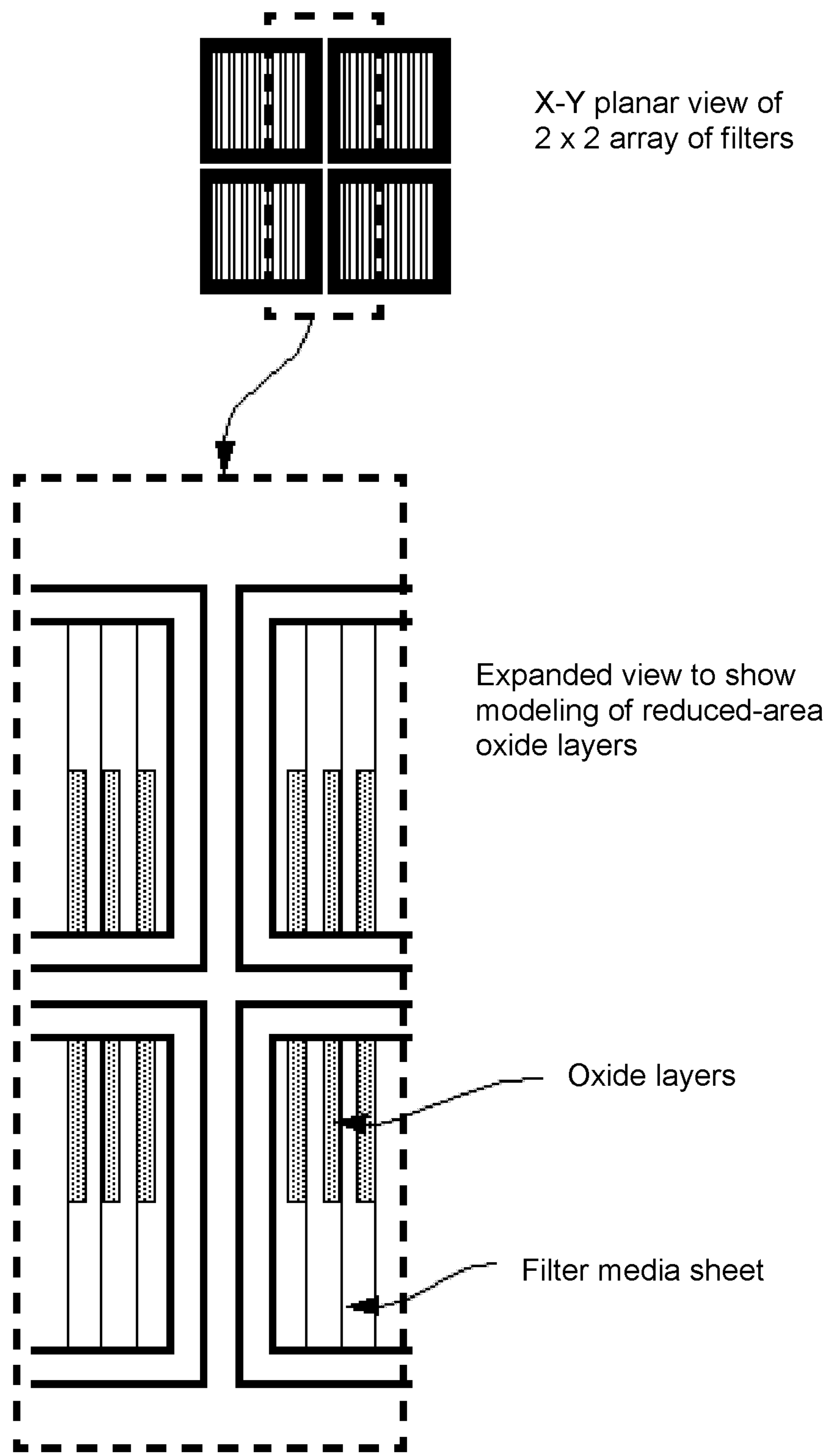

Figure 9. Example of plutonium dioxide distributed over a reduced area in filters.

The results in Table 11 show that a single filter containing up to 800 g of Pu-239 is not a criticality concern even for fully flooded and reflected conditions. No known historical data support filters ever having a fissile loading near 800 grams. However, this model demonstrates the conservatism in the models used in this evaluation and how the distribution of fissile material, as modeled, within the filter approaches an optimum configuration. These cases show the effects of mass and moderator on the reactivity of the system.

Table 11. Single overloaded Type 3 - 30.5 × 30.5 × 15.2-cm (12 × 12 × 6-in.) filter in soil with 100% water in filter gaps and fully saturated Subsurface Disposal Area soil as the reflector.

Case Name	Mass of Plutonium in the Form of Plutonium Dioxide in the Filter (g)	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
12 × 12 × 6_3a	300	0.8016 ± 0.0011	0.804
12 × 12 × 6_3b	400	0.8648 ± 0.0011	0.867
12 × 12 × 6_3c	500	0.9090 ± 0.0010	0.911
12 × 12 × 6_3d	600	0.9390 ± 0.0012	0.941
12 × 12 × 6_3e	700	0.9610 ± 0.0012	0.963
12 × 12 × 6_3f	800	0.9757 ± 0.0012	0.978
12 × 12 × 6_3g	900	0.9887 ± 0.0012	0.991
12 × 12 × 6_3h	1,000	1.0006 ± 0.0013	1.003
12 × 12 × 6_3i	1,100	1.0060 ± 0.0012	1.008
12 × 12 × 6_3j	1,200	1.0118 ± 0.0012	1.014

In the previously evaluated cases, closely packed ordered arrays of highly loaded optimally moderated filters were modeled. To achieve such configurations, burying the filters in cardboard boxes in an orderly stack would have been required. Then these boxes would have required enough integrity to preserve the materials comprising the filters, which is known not to be the case. The structural integrity of the filters themselves would have to have been maintained after the cardboard boxes disintegrated, which past retrieval operations have proved did not occur. All the filters would need to have been loaded at the maximum fissile loading and in close proximity, which is not probable.

The calculations performed for filters have shown that when filter spacing, diluent (soil addition), anticipated fissile mass, neutron absorber (B-10), compression (as a result of degradation or subsidence), and heterogeneity are taken into account, arrays of filters are far subcritical.

4.1.2 Filters in Drums

Another set of cases was evaluated that consisted of filters contained in 55-gal drums. The scenario considered includes an array of 55-gal drums housing filters in a close-pack arrangement. In these cases, the drum was included in the model. The purpose of this set of cases was to address the intact filters housed in intact drums, and show the negative effect that spacing has on reactivity. It is expected that if the filters were housed in either cardboard boxes or wooden boxes when disposed of, the containers would have deteriorated along with the filters. Past retrieval efforts and probing activities indicate that the drums have deteriorated. Though no intact drums are expected to be found, these cases show the effects of spacing that would be provided by intact drums.

The fissile loading per drum was modeled as 200 g of plutonium per drum in the form of PuO_2 dispersed on a single Type 2 filter in a single drum. Although only a single filter was modeled, the placement of the filters maximized interaction and is very conservative. Three configurations of drum arrays were modeled. The three examples of configurations modeled are shown in Figure 10. In each of the three configurations, the filters were offset within each drum to increase the interaction between the filters. Offsetting means that the filter in the drums on the upper layer were shifted down to the bottom of the drum and the filter in the drums on the bottom layer were shifted to the top of the drums. The filters were modeled as fully moderated with full-density water in the gaps between the filter media sheets. In all of the cases, the array was surrounded by fully saturated soil as a reflector and dispersed between the drums in the array. The remainder of the space in each drum outside of the filter was filled with saturated soil.

For Configuration A, the drums were modeled in a square-pitch $2 \times 2 \times 2$ arrangement with a single filter placed in each drum in an offset manner, as shown in Figure 10. In this configuration, each of the filters was rotated 45 degrees in each drum to evaluate interaction between the filters.

For Configuration B, the drums were also modeled in a square-pitch arrangement. In this case, the filters were offset to the sides of each drum to evaluate the reactivity of this configuration.

For Configuration C, a triangular-pitch array of four drums was evaluated with the filters offset, as depicted in Figure 10. This array was evaluated to determine the reactivity difference between this arrangement and the square-pitch variations. The results from these cases are given in Table 12.

As shown by these results, highly loaded filters are subcritical modeled in a drum. These cases demonstrate the negative effect of spacing (or geometry) on the reactivity of the system.

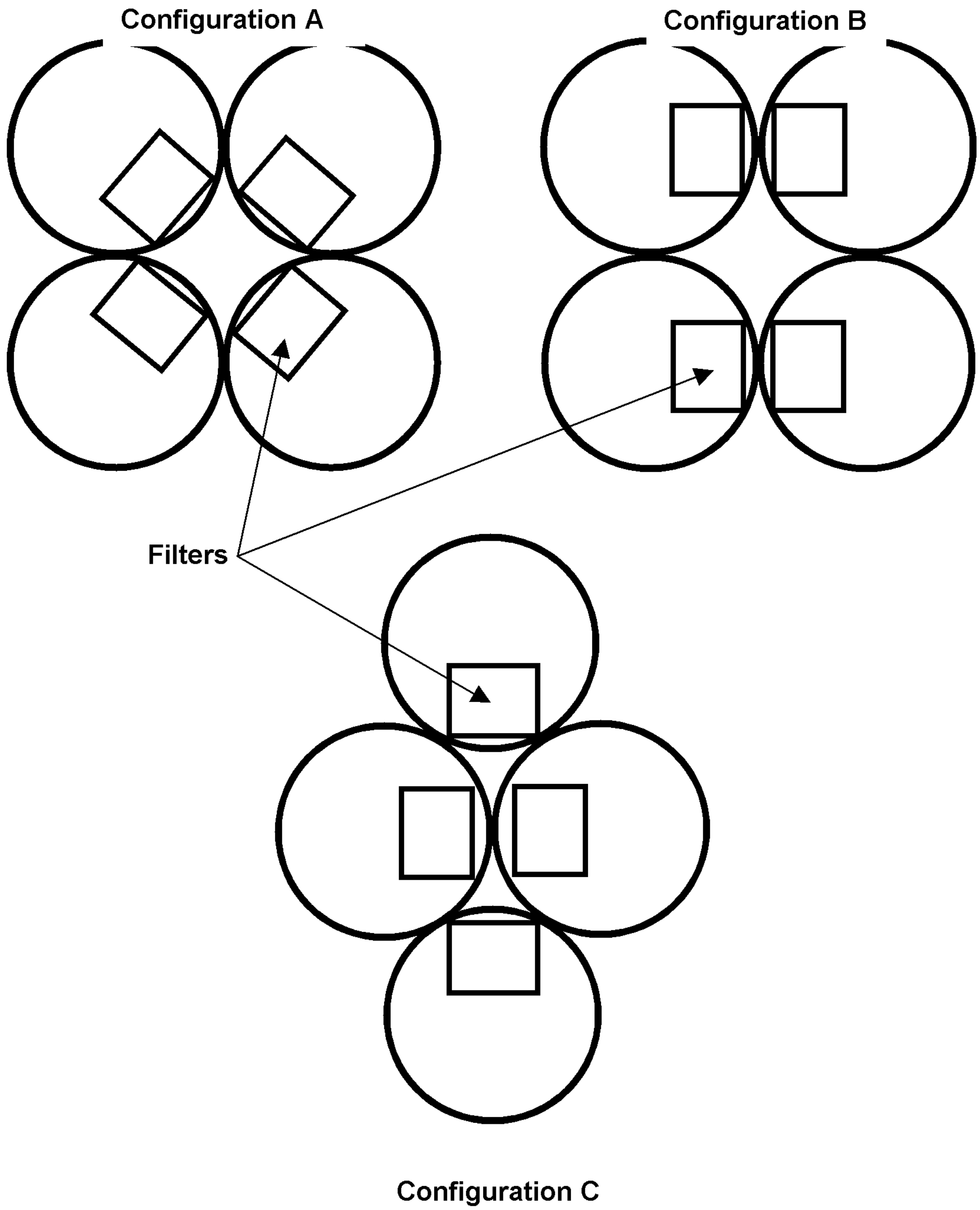

Figure 10. The x-y planar view of the drum arrays with a single filter per drum.

Table 12. 2 × 2 × 2 array of drums containing a Type 2 filter showing the reactivity effect from spacing when filters are housed in drums.[a]

Case Name	Configuration Modeled (from Figure 10)	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
drums_1a	A	0.9413 ± 0.0010	0.943
drums_1b	B	0.9344 ± 0.0011	0.937
drums_1c	C	0.9051 ± 0.0010	0.907

a. The array has 200 g of plutonium per filter in the drums. The filter gap regions contain full density water. The void in the drums outside the filters is filled with saturated soil as is the area outside the drums.

4.1.3 Filters in Large Wooden Boxes

Radioactive waste was shipped to the SDA from RFP in various types of containers. The previous sections evaluated filters that were shipped in either cardboard boxes or drums and were placed in the SDA. Another type of radioactive waste package used by RFP was the 1.2 × 2.1 × 1.2-m (4 × 7 × 4-ft) large wooden waste boxes. The fissile-loading limit per large waste box was 350 g of fissile material. In addition, a loading restriction limited the boxes from exceeding 5 g of fissile material per cubic foot. (However, it is believed that the requirement was not implemented until the 1989 timeframe.)[e]

The filter arrays that were modeled in the soil are enveloping for the possible configuration of first- and second-stage filters in the large wooden boxes. If no cubic foot in the box contained more than 5 g of plutonium and the box fissile-loading limit of 350 g was complied with, the distribution of the fissile material in the boxes would not be of concern.

A good argument can be made that any filter housed in a cardboard box under soil for that number of years would have decomposed and/or compressed and thus does not present a concern. This same argument could be made for the large wooden boxes (Thompson 1972). In addition, subsidence events at the SDA lend to the credibility of the argument that the boxes have experienced decomposition. Therefore, specific models were not developed for the large wooden boxes in this evaluation.

4.2 Graphite

Historical records (see footnote b) indicate that overloaded drums containing graphite as the waste matrix were discovered at RFP before shipment to the INEEL. Graphite is a waste byproduct of the process that was in use at RFP. Based on an estimate (see footnote b) of fissile material and graphite loaded at RFP for shipment to INEEL, the average loading from a sample of drums at RFP was determined to be 190 g of plutonium with the highest loading at 789 g of plutonium. In this data set, one point is identified as abnormal. A loading of 1,000 g of plutonium per waste drum was evaluated for this study. An estimate of 1,000 g of plutonium is bounding as compared to the drum information. Over 2,300 graphite drums have been assayed in aboveground storage at RWMC. No drum with a fissile loading grater than 380 g was found and only four drums contained greater than 200 g. Various plutonium in graphite configurations were evaluated with the results described below.

e. Vejvoda, Ed, Los Alamos Technical Associates, Letter to Bruce H. Becker, Idaho National Engineering and Environmental Laboratory, September 26, 2001, "Nuclear Safety – Waste Management," EV-L01039.

In the first set of cases, which envelop a single overloaded drum, reactivity was evaluated for a single drum containing 1,000 g of plutonium dispersed in graphite as PuO_2 at various densities. No water was modeled as interspersed in the waste matrix for this initial set of cases. The theoretical density of graphite used in the model was 2.25 g/cm^3. This is a very conservative density and gives bounding results for this configuration because the actual density of the graphite material will be much less because the graphite waste consists of intact or broken molds that will certainly have void between the pieces. The material was modeled in a sphere reflected by saturated soil. The spherical volume was limited by the equivalent volume of a single 55-gal drum. The results of this set of cases are given in Table 13.

Table 13. Sphere of graphite and plutonium dioxide with 1,000 g of plutonium in the form of plutonium dioxide representing a single overloaded drum.

Case Name	Radius of Plutonium Dioxide and Graphite Sphere (cm)	Density of Plutonium Dioxide (g/cm^3)	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
graphite_1a	5	2.17	0.3788 $\pm$ 0.0008	0.380
graphite_1b	10	0.271	0.4589 $\pm$ 0.0009	0.461
graphite_1c	15	0.080	0.5555 $\pm$ 0.0010	0.558
graphite_1d	20	0.034	0.6326 $\pm$ 0.0012	0.635
graphite_1e	25	0.017	0.6906 $\pm$ 0.0011	0.693
graphite_1f	30	0.010	0.7307 $\pm$ 0.0012	0.733
graphite_1g	35	0.006	0.7447 $\pm$ 0.0012	0.747
graphite_1h	37.35	0.005	0.7483 $\pm$ 0.0011	0.750

As shown by the results given in Table 13, a single drum overloaded with up to 1,000 g of plutonium in the form of PuO_2 and graphite will remain subcritical. These cases demonstrate the effects of mass and limited moderation provided by graphite in the limited volume of a drum. In the next set of cases, the effects of combining water into the graphite and plutonium system were evaluated.

In this set of cases, 1,000 g of plutonium in the form of PuO_2 and graphite were combined with water in various amounts. Once again, a spherical geometry was used. The amount of graphite present corresponds to the maximum amount that could be stored in a 55-gal drum. The density of the graphite in the sphere was reduced by 10, 20, 30, and 40%, with the void fraction being replaced with water. The PuO_2 was homogeneously dispersed over the entire volume of the sphere, which is extremely conservative since the plutonium would be on and in the waste in heterogeneous manner. The results of these cases are given in Table 14.

As shown by these results, even though water is introduced into the system, the 1,000 g of plutonium in the form of PuO_2 does not form a critical system. However, the calculation does show that peak reactivity occurs with a 10% volume fraction that is filled with water. The maximum volume fraction of graphite in a drum (graphite molds) would be about 40 to 50%. A 20% void fraction, which is near the peak reactivity was conservatively chosen for the remainder of the cases. These cases also demonstrate the effects of moderation and mass on the reactivity and the subcriticality of the system.

Table 14. Sphere of graphite, water, and plutonium dioxide with 1,000 g of plutonium in the form of plutonium dioxide representing a single overloaded drum.

Case Name	Volume Fraction Occupied by Water (%)	Hydrogen to Plutonium Ratio	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
graphite_2a	10	596	0.9520 ± 0.0010	0.954
graphite_2b	20	1,342	0.9422 ± 0.0008	0.944
graphite_2c	30	2,300	0.8678 ± 0.0007	0.869
graphite_2d	40	3,578	0.7600 ± 0.0005	0.761

A single intact drum loaded with various fissile material amounts was also evaluated. This drum was reflected by fully saturated soil. In each of these cases, the drum was modeled completely full of graphite at 80% of its full density with a 20% void fraction that was modeled filled with water. In each case, the PuO_2 was modeled as homogeneously dispersed over the entire drum. These assumptions are very conservative. The results of this evaluation are given in Table 15.

Table 15. Drum of graphite, water, and plutonium dioxide with varied gram amounts of plutonium in the form of plutonium dioxide in a single overloaded drum.

Case Name	Quantity of Plutonium in the Drum (g)	Hydrogen to Plutonium Ratio	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
graphite_4a1a	200	6,085	0.3391 ± 0.0004	0.400
graphite_4a1b	400	3,042	0.5501 ± 0.0006	0.551
graphite_4a1c	600	2,028	0.6921 ± 0.0007	0.693
graphite_4a1d	800	1,521	0.7978 ± 0.0008	0.799
graphite_4a1e	1,000	1,217	0.8738 ± 0.0010	0.876
graphite_4a1f	1,200	1,014	0.9320 ± 0.0010	0.934

As shown by the results of the single drum cases, the 1,000 g of plutonium in a single drum of 80% density graphite with the 20% void fraction being filled with water does not yield a critical system. Once again, this is a very conservative model with the PuO_2 modeled as dispersed homogeneously throughout the drum in the graphite matrix. In reality, the plutonium likely would be dispersed in a more heterogeneous manner in cracks and fissures in the graphite molds.

A case was also evaluated in which the model consisted of PuO_2 dispersed in a layer over a spherical "chunks" of graphite. These calculations were performed to demonstrate the negative reactivity effect from heterogeneity. A square-pitched array of these spheres was then modeled filling up the volume in a drum. The void space in the drum was filled with water. The mass of the PuO_2 associated with the 1,000 g of plutonium was spread evenly over the total surface of the spheres in this array. In other words, the thickness of the PuO_2 layer coating each sphere of graphite was determined by evenly dividing the entire volume of the PuO_2 (represented by 1,000 g of plutonium) over the total spheres present. In this case, the spheres were modeled as having a 2.5-cm (1-in.) radius. The array contained

1,547 spheres with a layer of PuO_2 7.18×10^{-4} cm (2.8×10^{-4} in.) thick on each sphere. The spheres were modeled as nearly touching in the drum. The $k_{eff} + 2\sigma$ for this case was calculated to be 0.719. These cases demonstrate the negative effect of the heterogeneous nature of the waste.

A last set of cases was evaluated to determine the calculated k_{eff} for various drum arrays containing a single drum with 1,000 g of plutonium with graphite waste material. The remaining drums in the array contained 200 g of plutonium in the form of oxide in graphite waste material. The graphite was modeled as 80% of theoretical density with the 20% void fraction being filled with water. Variously sized drum arrays were modeled as fully reflected by water-saturated soil. The results of these cases are given in Table 16. These calculations show that even with a large improbable array of highly loaded moderated drums, this waste form is subcritical. Another study (Nielsen 2002b) has shown that an array of more than 500 graphite drums is subcritical with 380 g of Pu-239 and 118 kg (260 lb) of graphite in each drum.

Table 16. Arrays of drums in soil with 1,000 g of plutonium in a single drum of graphite waste material in the form of plutonium dioxide, water, and 20%-density graphite.[a]

Case Name	Size of Array Modeled	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
graphite_4a3	$3 \times 3 \times 2$	0.9008 ± 0.0008	0.902
graphite_4b3	$3 \times 2 \times 2$	0.8941 ± 0.0009	0.896
graphite_4c3	$2 \times 2 \times 2$	$0.8906 + 0.0009$	0.892
graphite_4d3	$2 \times 2 \times 1$	$0.8838 + 0.0008$	0.885

a. The remaining drums in the array are modeled with 200 g of plutonium per drum.

The physical form of the graphite waste consists of broken molds or pieces of molds that inherently make optimal conditions not possible in belowground waste. The fissile material in the waste is not homogeneous, optimal moderation cannot occur without intentional mechanical force, and the waste matrix itself is a diluent for drum-sized volumes. The addition of soil, which will occur with drum degradation, will only reduce reactivity.

4.3 Magnesium Oxide

Magnesium oxide is a waste byproduct of a process that was in use at RFP. Assaying of drums in the aboveground storage facilities at the RWMC has shown the maximum MgO drum to contain less than 200g of fissile material. There was concern that this waste form could have a potential for being overloaded due to the RFP process history and initial assay of aboveground waste drums at RWMC. Calculations were performed to evaluate this waste form and others that are enveloped.

For this study, a loading of 1,500 g of plutonium in a single waste drum was evaluated. Various configurations were evaluated to determine the calculated k_{eff}. These model configurations and the associated results are described below.

Heels from the bottoms of crucibles were evaluated in the modeling. The actual heels were likely hemispherical in shape and are likely to be broken. The discrete pieces would preclude the fissile material from being dispersed homogeneously in this waste matrix and, therefore, would decrease the likelihood of a critical system being formed.

In the first set of cases, which envelops a single overloaded drum, the reactivity was evaluated as 1,500 g of plutonium homogeneously dispersed in MgO with the PuO_2 density varied. The theoretical density of MgO used was 3.58 g/cm^3. Again, this is a very conservative assumption and will give bounding results for this configuration. The material was modeled in a spherical form reflected by saturated soil. The results of this set of cases are given in Table 17.

As shown by the results given in Table 17, a single drum overloaded with up to 1,500 g of plutonium in the form of PuO_2 and MgO will remain subcritical. However, to a limited degree (as a result of the moderating material being MgO, which is a poor moderator), these cases show the effects of mass and lack of moderation on the reactivity of the system. In the next set of cases, the effects of combining water into the MgO and plutonium system were evaluated.

In this set of cases, 1,500 g of plutonium in the form of PuO_2 and MgO were combined with various amounts of water. Again, a spherical geometry was used. The density of the MgO was reduced from 10 to 50% incrementally with the void fraction being filled with water. The PuO_2 was dispersed over the entire volume of the sphere. The results of these cases are given in Table 18.

Table 17. Sphere of magnesium oxide and plutonium dioxide with 1,500 g of plutonium in the form of plutonium dioxide representing a single overloaded drum.

Case Name	Radius of Plutonium Dioxide and Magnesium Oxide Sphere (cm)	Density of Plutonium Dioxide (g/cm^3)	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
mgo_1a	5	3.25	0.3759 $\pm$ 0.0006	0.377
mgo_1b	10	0.41	0.2979 $\pm$ 0.0007	0.299
mgo_1c	15	0.12	0.3213 $\pm$ 0.0007	0.323
mgo_1d	20	0.05	0.3554 $\pm$ 0.0008	0.357
mgo_1e	25	0.026	0.3884 $\pm$ 0.0007	0.390
mgo_1f	30	0.015	0.4292 $\pm$ 0.0009	0.431
mgo_1g	35	0.009	0.4748 $\pm$ 0.0009	0.476
mgo_1h	37.35	0.008	0.4958 $\pm$ 0.0008	0.497

Table 18. Sphere of magnesium oxide, water, and plutonium dioxide with 1,500 g of plutonium in the form of plutonium dioxide representing a single overloaded drum.

Case Name	Volume Fraction Occupied by Water (%)	Ratio of Hydrogen to Plutonium	$k_{eff} \pm 1\sigma$	$k_{eff} + 2\sigma$
mgo_2a	10	450	0.8315 $\pm$ 0.0009	0.833
mgo_2b	20	1,014	0.8953 $\pm$ 0.0008	0.897
mgo_2c	30	1,738	0.8706 $\pm$ 0.0008	0.872
mgo_2d	40	2,704	0.8033 $\pm$ 0.0006	0.805
mgo_2e	50	4,057	0.7046 $\pm$ 0.0005	0.706

These cases are very conservative because the plutonium was modeled as if dispersed homogeneously throughout the MgO matrix, when in reality, because of the nature of the process that generated the waste (molds), it would be in a more heterogeneous form. Magnesium oxide is similar to SiO_2 in that it has a low absorption neutron cross section. Therefore, a larger system is necessary to achieve a critical system and the dispersion of the oxide causes the reactivity to be lower.

The physical form of the MgO waste comprises broken molds and or pieces of molds that inherently make optimal conditions not possible in belowground waste. The fissile material in the waste is not homogeneous; therefore, optimal moderation cannot occur without mechanical force and the waste matrix itself is a diluent for drum-sized quantities. The addition of soil that will occur with drum degradation will only further reduce reactivity.

5. SUMMARY

In order for criticality to occur in the SDA, several unlikely concurrent parameters must exist. There must be sufficient fissile mass; the fissile mass must be at or near the optimum concentration; the fissile mass must be in or nearly in an optimal geometry; there must be optimal or near optimal moderation (Criticality in the SDA is not possible without moderation. The fissile masses required for an unmoderated criticality are in the tens of kilograms and are not credible); near optimal reflection; and the fissile mass must be in a waste matrix that lacks diluent and neutron absorber, which are known to exist in most waste matrices. Achieving criticality with the fissile masses expected in the waste forms is not credible even with the introduction of moderator.

Various configurations involving three waste matrices of concern, glovebox HEPA filters, graphite, and MgO, are discussed in this study. The parameters affecting criticality were investigated to determine the effects on the subcriticality of the SDA. As shown by some of the models evaluated, when very conservative idealized assumptions are used, k_{eff}s approaching critical can be can be postulated for ordered arrays of heavily loaded homogenized HEPA filters and highly overloaded graphite and MgO drums. When credit is taken for expected mass of fissile material, presence of moderating material, geometrical configuration, presence of diluents and neutron absorbers, reflective conditions, and concentration and distribution of the fissile material, criticality is shown to be not possible. The varied parameters and the negative effects resulting from realistic assumptions are summarized in Table 19.

Note: in most of the cases, unless otherwise specified, the models for filters consisted of a 2 × 1 × 2 array of Type 2 filters with 200 g of plutonium loading per filter. The filters in the array have a 1-cm (0.4-in.) edge-to-edge spacing in a fully saturated SDA soil system. The density of the oxide on the filter media sheets was modeled as 2 g/cm^3.

Table 19. Summary of Δk for calculated k_{eff} for various model permutations.

Parameter Varied	Maximum $k_{eff} + 2\sigma$ in Set of Cases	Minimum $k_{eff} + 2\sigma$ in Set of Cases	Δk Between Maximum and Minimum
Spacing: Edge-to-edge spacing between filters in 2 × 1 × 2 array (with spacing from 1 to 20-cm [0.4 to 7.8-in.])	0.953	0.734	0.219
Mass: 50 g per filter with 1-cm (0.4-in.) edge-to-edge spacing in 2 × 2 × 2, 3 × 3 × 3, 4 × 4 × 4, 5 × 5 × 5, and 6 × 6 × 6 arrays	0.892	0.665	0.227
Diluent and moderation: Subsurface Disposal Area (SDA) soil in filters (40% water volume fraction [wvf]) with the wvf in soil in filters varying from 100 to 0% in 2 × 2 × 3 array	0.980	0.764	0.216
Diluent and moderation: Filter gaps filled with soil-water combinations, 90% wvf with 10% soil to 50% wvf with 50% soil, in 2 × 2 × 3 array	0.927	0.793	0.134
Neutron absorber: Weight fraction of	0.953	0.909	0.044

Table 19. (continued).

Parameter Varied	Maximum $k_{eff} + 2\sigma$ in Set of Cases	Minimum $k_{eff} + 2\sigma$ in Set of Cases	Δk Between Maximum and Minimum
B-10 in water in filter gaps, 0 (i.e., no B-10 from SDA soil) to 8.75×10^{-6} (i.e., 100% of B-10 from SDA soil) in $2 \times 1 \times 2$ array			
Moderation: Reduced gap spacing between filter media sheets, 100 to 25% gap in $2 \times 1 \times 2$ array	0.953	0.845	0.108
Concentration and distribution: Reduction in area over filter media sheet in which PuO_2 is distributed, 100 to 10% of area in $2 \times 1 \times 2$ array	0.953	0.564	0.389
Mass: Various overload quantities in a single filter, 1,000 g to 300 g of plutonium	1.003	0.804	0.199
Mass: Single overloaded graphite drum with 1,000 g of plutonium modeled as PuO_2 dispersed over entire volume of drum with water or as discrete layers of PuO_2 over spherical chunks of graphite	0.876	0.719	0.157

6. CONCLUSIONS

As shown by the study, a postulated criticality in the SDA is dependent on numerous parameters that affect criticality. These parameters include the amount of fissile mass present, amount of moderator present, the geometrical configurations, the presence of diluents or neutron absorbers, the reflection conditions surrounding the fissile systems, and the concentration or distribution of the fissile material in the waste. Most of these parameters would need to be optimized in some combination to achieve a critical system. As deviations from optimum conditions occur, the reactivity of the systems decreases dramatically.

As stated earlier, although very unlikely, the potential exists for a waste package to contain an unsafe fissile mass. However, it would be extremely difficult for packages with even kilogram quantities of fissile material to achieve criticality. Also, all the scenarios require near-optimum moderation (i.e., water).

The models evaluated in this study were designed to show the effects that various parameters have on the reactivity of the system.

6.1.1 Fissile Mass

As shown by the filter cases loaded with 50 g of Pu-239 each, even with the large number of filters, the systems were shown to remain subcritical. These cases included near-optimum moderation and near-homogeneous distribution of fissile material. As the masses in the filters were increased to the maximum expected fissile loading with near-optimum moderation, postulated criticality scenarios were theoretically achievable in the absence of the negative reactivity effects from the other parameters. The expected configuration in the SDA does not lend itself to such idealized configurations.

6.1.2 Moderator

When deviation from near-optimum moderation occurs, more fissile material is necessary to postulate a critical system. Water is key to postulating a criticality in the SDA. Cases were performed that showed the negative effect of moderator exclusion. The scenarios evaluated (1) compressed-filters and (2) intrusion of soil and water into the air gap in the filters. Water also was included in the graphite and MgO cases to show how the addition of water increases reactivity. In the most reactive postulated models, the water was dispersed in the systems in an unrealistic nearly optimum configuration. As deviations from this near-optimum configuration occurred, the reactivity of the systems decreased.

6.1.3 Geometry

The models evaluated in this study consist of ordered arrays pertaining to the geometrical configuration of the filters and the near-homogeneous distribution of fissile materials in the waste matrices. In these idealistic computational models, reactive systems can be postulated. However, in realistic burial conditions, the reactivity of the systems would be much less. For instance, as the geometry of a filter array becomes more random and the space between filters is increased, the reactivity of the system decreases. The reactivity of the system also decreases as the fissile material distribution becomes less ordered.

6.1.4 Diluents and Neutron Absorbers

As shown in the models, the introduction of diluents, which absorbs neutrons from the system and allows for exclusion of moderator, has a large negative effect on the reactivity.

6.1.5 Reflection

The soil and waste are reflectors, but they are not as effective as water. Voids in the waste and less dense waste materials will certainly have a negative effect on reactivity. Dry soil was shown to be a less effective reflector than water saturated soil.

6.1.6 Concentration and Distribution of Fissile Material

The distribution and concentration of fissile material has a large effect on reactivity. Assuming fissile material throughout each filter media sheet within a filter is very conservative. Models showed a large negative reactivity effect when more realistic filters with decreased fissile areas were evaluated. As shown by the models, as the concentration and distribution of the fissile material deviates from near optimum conditions the reactivity of the system reactivity decreases.

6.1.7 Conclusion

The conclusion of this report is that a criticality in the SDA, as currently configured is not credible. The models developed for this study show the correlation between the parameters affecting criticality and the effects of these parameters on the reactivity on the system. This study shows that when the effects of realism are incorporated into idealized calculational models that simulate actual waste conditions, the SDA is subcritical and will remain subcritical during postulated water flooding scenarios.

7. REFERENCES

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Appendix A

Excel Spreadsheets—Calculated Inputs for Computational Model

Appendix A

Excel Spreadsheets—Calculated Inputs for Computational Model

The spreadsheets in this appendix contain the mathematical calculations to produce the input parameters used in the computational models.

Table A-1. Calculational data for a 20.3 × 20.3 × 15.2-cm (8 × 8 × 6-in.) filter.

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Z length of Filter Media (cm)	14.9225	
Y Length of Filter Media (cm)	16.51	
Area of One Sheet (cm2)	246.370475	
# of Sheets in Filter	32	
Total Area of Filter Media (cm2)	7883.8552	
MA Pu239(95%) Pu240 (5%)	239.1021	
MA Pu239	239.0521	
MA Pu240	240.0538	
MA Pu239(95%) Pu240 (5%)O2	271.1009	
Density of PuO2 (g/cm3)	11.46	
Grams of Pu (g)	200	150
Grams of PuO2 (g)	226.77	170.07

Gram Density of PuO2	1	2	3	4	5	6	7	8
Mass of PuO2 (g)	226.77	226.77	226.77	226.77	226.77	226.77	226.77	226.77
Volume of PuO2 (cm3)	226.77	113.38	75.59	56.69	45.35	37.79	32.40	28.35
N^{239}	2.1107E-03	4.2214E-03	6.3321E-03	8.4428E-03	1.0553E-02	1.2664E-02	1.4775E-02	1.6886E-02
N^{240}	1.1063E-04	2.2125E-04	3.3188E-04	4.4250E-04	5.5313E-04	6.6375E-04	7.7438E-04	8.8500E-04
N^{O}	4.4426E-03	8.8853E-03	1.3328E-02	1.7771E-02	2.2213E-02	2.6656E-02	3.1098E-02	3.5541E-02
N^{H}	6.0911E-02	5.5088E-02	4.9265E-02	4.3441E-02	3.7618E-02	3.1795E-02	2.5972E-02	2.0148E-02
N^{O}	3.0456E-02	2.7544E-02	2.4632E-02	2.1721E-02	1.8809E-02	1.5897E-02	1.2986E-02	1.0074E-02
$N^{O\ Tot}$	3.4898E-02	3.6429E-02	3.7960E-02	3.9491E-02	4.1022E-02	4.2553E-02	4.4084E-02	4.5615E-02
N^{Tot}	9.8031E-02	9.5960E-02	9.3889E-02	9.1818E-02	8.9747E-02	8.7676E-02	8.5605E-02	8.3534E-02
H/Pu Ratio	28.86	13.05	7.78	5.15	3.56	2.51	1.76	1.19
Mass of PuO2 (g)	170.07	170.07	170.07	170.07	170.07	170.07	170.07	170.07
Volume of PuO2 (cm3)	170.07	85.04	56.69	42.52	34.01	28.35	24.30	21.26
Thickness of PuO2 Layer Single Side of Media 200g PuO2	0.02876	0.01438	0.00959	0.00719	0.00575	0.00479	0.00411	0.00360
Thickness of PuO2 Layer Both Sides of Media 200 g PuO2	0.01438	0.00719	0.00479	0.00360	0.00288	0.00240	0.00205	0.00180
Thickness of PuO2 Layer Single Side of Media 150 g PuO2	0.02157	0.01079	0.00719	0.00539	0.00431	0.00360	0.00308	0.00270
Thickness of PuO2 Layer Both Sides of Media 150 g PuO2	0.01079	0.00539	0.00360	0.00270	0.00216	0.00180	0.00154	0.00135
Gram Density of PuO2	1	2	3	4	5	6	7	8
Coordinates								
200 g Single Layer +x from Media of +x = 0.0381	0.06686	0.05248	0.04769	0.04529	0.04385	0.04289	0.04221	0.04170
150 g Single Layer +x from Media of +x = 0.0381	0.05967	0.04889	0.04529	0.04349	0.04241	0.04170	0.04118	0.04080
200 g Double Layer +x from Media of +x = 0.0	0.01438	0.00719	0.00479	0.00360	0.00288	0.00240	0.00205	0.00180
200 g Double Layer +x of Media	0.05248	0.04529	0.04289	0.04170	0.04098	0.04050	0.04015	0.03990
200 g Double Layer +x from Media of +x	0.06686	0.05248	0.04769	0.04529	0.04385	0.04289	0.04221	0.04170
200 g Double Layer +x of water channel for +x PuO2	0.52873	0.52154	0.51914	0.51795	0.51723	0.51675	0.51640	0.51615
150 g Double Layer +x from Media of +x = 0.0	0.01079	0.00539	0.00360	0.00270	0.00216	0.00180	0.00154	0.00135
150 g Double Layer +x of Media	0.04889	0.04349	0.04170	0.04080	0.04026	0.03990	0.03964	0.03945
150 g Double Layer +x from Media of +x	0.05967	0.04889	0.04529	0.04349	0.04241	0.04170	0.04118	0.04080
150 g Double Layer +x of water channel for +x PuO2	0.52514	0.51974	0.51795	0.51705	0.51651	0.51615	0.51589	0.51570

Gram Density of PuO2	9	10	11	11.46
Mass of PuO2 (g)	226.77	226.77	226.77	226.77
Volume of PuO2 (cm3)	25.20	22.68	20.62	19.79
N^{239}	1.8996E-02	2.1107E-02	2.3218E-02	2.4188E-02
N^{240}	9.9563E-04	1.1063E-03	1.2169E-03	1.2678E-03
N^{O}	3.9984E-02	4.4426E-02	4.8869E-02	5.0913E-02
N^{H}	1.4325E-02	8.5019E-03	2.6787E-03	0.0000E+00
N^{O}	7.1626E-03	4.2510E-03	1.3393E-03	0.0000E+00
$N^{O\ Tot}$	4.7146E-02	4.8677E-02	5.0208E-02	5.0913E-02
N^{Tot}	8.1463E-02	7.9392E-02	7.7321E-02	7.6369E-02
	0.75	0.40	0.12	0.00
Mass of PuO2 (g)	170.07	170.07	170.07	170.07
Volume of PuO2 (cm3)	18.90	17.01	15.46	14.84
Thickness of PuO2 Layer Single Side of Media 200g PuO2	0.00320	0.00288	0.00261	0.00251
Thickness of PuO2 Layer Both Sides of Media 200 g PuO2	0.00160	0.00144	0.00131	0.00125
Thickness of PuO2 Layer Single Side of Media 150 g PuO2	0.00240	0.00216	0.00196	0.00188
Thickness of PuO2 Layer Both Sides of Media 150 g PuO2	0.00120	0.00108	0.00098	0.00094
Gram Density of PuO2	9	10	11	11.46
Coordinates				
200 g Single Layer +x from Media of +x = 0.0381	0.04130	0.04098	0.04071	0.04061
150 g Single Layer +x from Media of +x = 0.0381	0.04050	0.04026	0.04006	0.03998
200 g Double Layer +x from Media of +x = 0.0	0.00160	0.00144	0.00131	0.00125
200 g Double Layer +x of Media	0.03970	0.03954	0.03941	0.03935
200 g Double Layer +x from Media of +x	0.04130	0.04098	0.04071	0.04061
200 g Double Layer +x of water channel for +x PuO2	0.51595	0.51579	0.51566	0.51560
150 g Double Layer +x from Media of +x = 0.0	0.00120	0.00108	0.00098	0.00094
150 g Double Layer +x of Media	0.03930	0.03918	0.03908	0.03904
150 g Double Layer +x from Media of +x	0.04050	0.04026	0.04006	0.03998
150 g Double Layer +x of water channel for +x PuO2	0.51555	0.51543	0.51533	0.51529

Table A-2. Calculational data for a 30.5 × 30.5 × 15.2-cm (12 × 12 × 6-in.) filter.

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Y length of Filter Media (cm)	26.67	
Z Length of Filter Media (cm)	14.9225	
Area of One Sheet (cm2)	397.983075	
# of Sheets in Filter	52	
Total Area of Filter Media (cm2)	20695.1199	
MA Pu239	239.0521	
MA Pu240	240.0538	
MA Pu239(95%) Pu240 (5%)	239.1021	
MA Pu239(95%) Pu240 (5%)O2	271.1009	
Density of PuO2 (g/cm3)	11.46	
Grams of Pu (g)	200	150
Grams of PuO2 (g)	226.77	170.07

Gram Density of PuO2	1	2	3	4	5	6	7	8	9	10	11	11.46
Mass of PuO2 (g)	226.77	226.77	226.77	226.77	226.77	226.77	226.77	226.77	226.77	226.77	226.77	226.77
Volume of PuO2 (cm3)	226.77	113.38	75.59	56.69	45.35	37.79	32.40	28.35	25.20	22.68	20.62	19.79
N^{239}	2.1107E-03	4.2214E-03	6.3321E-03	8.4428E-03	1.0553E-02	1.2664E-02	1.4775E-02	1.6886E-02	1.8996E-02	2.1107E-02	2.3218E-02	2.4188E-02
N^{240}	1.1063E-04	2.2125E-04	3.3188E-04	4.4250E-04	5.5313E-04	6.6375E-04	7.7438E-04	8.8500E-04	9.9563E-04	1.1063E-03	1.2169E-03	1.2678E-03
N^{O}	4.4426E-03	8.8853E-03	1.3328E-02	1.7771E-02	2.2213E-02	2.6656E-02	3.1098E-02	3.5541E-02	3.9984E-02	4.4426E-02	4.8869E-02	5.0913E-02
N^{H}	6.0911E-02	5.5088E-02	4.9265E-02	4.3441E-02	3.7618E-02	3.1795E-02	2.5972E-02	2.0148E-02	1.4325E-02	8.5019E-03	2.6787E-03	0.0000E+00
N^{O}	3.0456E-02	2.7544E-02	2.4632E-02	2.1721E-02	1.8809E-02	1.5897E-02	1.2986E-02	1.0074E-02	7.1626E-03	4.2510E-03	1.3393E-03	0.0000E+00
$N^{O\ Tot}$	3.4898E-02	3.6429E-02	3.7960E-02	3.9491E-02	4.1022E-02	4.2553E-02	4.4084E-02	4.5615E-02	4.7146E-02	4.8677E-02	5.0208E-02	5.0913E-02
N^{Tot}	9.80306E-02	9.59596E-02	9.38887E-02	9.18178E-02	8.97469E-02	8.76760E-02	8.56051E-02	8.35342E-02	8.14632E-02	7.93923E-02	7.73214E-02	7.63688E-02
H/Pu Ratio	28.86	13.05	7.78	5.15	3.56	2.51	1.76	1.19	0.75	0.40	0.12	0.00
Mass of PuO2 (g)	170.07	170.07	170.07	170.07	170.07	170.07	170.07	170.07	170.07	170.07	170.07	170.07
Volume of PuO2 (cm3)	170.07	85.04	56.69	42.52	34.01	28.35	24.30	21.26	18.90	17.01	15.46	14.84
Thickness of PuO2 Layer Single Side of Media 200g PuO2	0.01096	0.00548	0.00365	0.00274	0.00219	0.00183	0.00157	0.00137	0.00122	0.00110	0.00100	0.00096
Thickness of PuO2 Layer Both Sides of Media 200 g PuO2	0.00548	0.00274	0.00183	0.00137	0.00110	0.00091	0.00078	0.00068	0.00061	0.00055	0.00050	0.00048
Thickness of PuO2 Layer Single Side of Media 150 g PuO2	0.00822	0.00411	0.00274	0.00205	0.00164	0.00137	0.00117	0.00103	0.00091	0.00082	0.00075	0.00072
Thickness of PuO2 Layer Both Sides of Media 150 g PuO2	0.00411	0.00205	0.00137	0.00103	0.00082	0.00068	0.00059	0.00051	0.00046	0.00041	0.00037	0.00036

Gram Density of PuO2	1	2	3	4	5	6	7	8	9	10	11	11.46
Coordinates												
200 g Single Layer +x from Media of +x = 0.0381	0.04906	0.04358	0.04175	0.04084	0.04029	0.03993	0.03967	0.03947	0.03932	0.03920	0.03910	0.03906
150 g Single Layer +x from Media of +x = 0.0381	0.04632	0.04221	0.04084	0.04015	0.03974	0.03947	0.03927	0.03913	0.03901	0.03892	0.03885	0.03882
200 g Double Layer +x from Media of +x = 0.0	0.00548	0.00274	0.00183	0.00137	0.00110	0.00091	0.00078	0.00068	0.00061	0.00055	0.00050	0.00048
200 g Double Layer +x of Media	0.04358	0.04084	0.03993	0.03947	0.03920	0.03901	0.03888	0.03878	0.03871	0.03865	0.03860	0.03858
200 g Double Layer +x from Media of +x	0.04906	0.04358	0.04175	0.04084	0.04029	0.03993	0.03967	0.03947	0.03932	0.03920	0.03910	0.03906
200 g Double Layer +x of water channel for +x PuO2	0.51983	0.51709	0.51618	0.51572	0.51545	0.51526	0.51513	0.51503	0.51496	0.51490	0.51485	0.51483
150 g Double Layer +x from Media of +x = 0.0	0.00411	0.00205	0.00137	0.00103	0.00082	0.00068	0.00059	0.00051	0.00046	0.00041	0.00037	0.00036
150 g Double Layer +x of Media	0.04221	0.04015	0.03947	0.03913	0.03892	0.03878	0.03869	0.03861	0.03856	0.03851	0.03847	0.03846
150 g Double Layer +x from Media of +x	0.04632	0.04221	0.04084	0.04015	0.03974	0.03947	0.03927	0.03913	0.03901	0.03892	0.03885	0.03882
150 g Double Layer +x of water channel for +x PuO2	0.51846	0.51640	0.51572	0.51538	0.51517	0.51503	0.51494	0.51486	0.51481	0.51476	0.51472	0.51471

Table A-3. Calculational data for an overloaded 30.5 × 30.5 × 15.2-cm (12 × 12 × 6-in.) filter.

Y length of Filter Media (cm)	26.67	
Z Length of Filter Media (cm)	14.9225	
Area of One Sheet (cm2)	397.983075	
# of Sheets in Filter	52	
Total Area of Filter Media (cm2)	20695.1199	
MA Pu239(95%) Pu240 (5%)	239.1021	
MA Pu239(95%) Pu240 (5%)O2	271.1009	
Density of PuO2 (g/cm3)	11.46	
Grams of Pu (g)	200	150
Grams of PuO2 (g)	226.77	170.07
Gram Density of PuO2	2	
Mass of PuO2 (g)	226.77	
Volume of PuO2 (cm3)	113.38	
N^{239}	4.2205E-03	
N^{240}	2.2213E-04	
N^{O}	8.8853E-03	
N^{H}	5.5088E-02	
N^{O}	2.7544E-02	
$N^{O\ Tot}$	3.6429E-02	
N^{Tot}	9.59596E-02	
H/Pu Ratio	13.05	

Mass of Pu (g)	200.00	300.00	400.00	500.00	600.00	700.00	800.00	900.00
Mass of PuO_2 (g)	226.77	340.15	453.53	566.91	680.30	793.68	907.06	1020.45
Volume of PuO_2 (cm^3)	113.38	170.07	226.77	283.46	340.15	396.84	453.53	510.22
Thickness of PuO2 Layer Single Side of Media 200g PuO2	0.00548	0.00822	0.01096	0.01370	0.01644	0.01918	0.02191	0.02465
Thickness of PuO2 Layer Both Sides of Media 200 g PuO2	0.00274	0.00411	0.00548	0.00685	0.00822	0.00959	0.01096	0.01233
200 g Single Layer +x from Media of +x = 0.0381	0.04358	0.04632	0.04906	0.05180	0.05454	0.05728	0.06001	0.06275

Mass of Pu (g)	1000.00	1100.00	1200.00	1300.00	1400.00	1500.00
Mass of PuO_2 (g)	1133.83	1247.21	1360.59	1473.98	1587.36	1700.74
Volume of PuO_2 (cm^3)	566.91	623.61	680.30	736.99	793.68	850.37
Thickness of PuO2 Layer Single Side of Media 200g PuO2	0.02739	0.03013	0.03287	0.03561	0.03835	0.04109
Thickness of PuO2 Layer Both Sides of Media 200 g PuO2	0.01370	0.01507	0.01644	0.01781	0.01918	0.02055
200 g Single Layer +x from Media of +x = 0.0381	0.06549	0.06823	0.07097	0.07371	0.07645	0.07919

Table A-4. Subsurface Disposal Area soil compositions.

	WVF	0	0.1	0.2	0.3	0.4
Element						
Si		1.0034E-02	1.0034E-02	1.0034E-02	1.0034E-02	1.0034E-02
Al		2.2387E-03	2.2387E-03	2.2387E-03	2.2387E-03	2.2387E-03
Fe		5.1263E-04	5.1263E-04	5.1263E-04	5.1263E-04	5.1263E-04
Ca		6.3198E-04	6.3198E-04	6.3198E-04	6.3198E-04	6.3198E-04
K		6.1135E-04	6.1135E-04	6.1135E-04	6.1135E-04	6.1135E-04
Mg		4.1109E-04	4.1109E-04	4.1109E-04	4.1109E-04	4.1109E-04
Na		4.2591E-04	4.2591E-04	4.2591E-04	4.2591E-04	4.2591E-04
Ti		8.2025E-05	8.2025E-05	8.2025E-05	8.2025E-05	8.2025E-05
Mn		1.1108E-05	1.1108E-05	1.1108E-05	1.1108E-05	1.1108E-05
B11		1.3781E-05	1.3781E-05	1.3781E-05	1.3781E-05	1.3781E-05
H		0.0000E+00	6.6855E-03	1.3371E-02	2.0056E-02	2.6742E-02
O		2.5964E-02	2.9307E-02	3.2649E-02	3.5992E-02	3.9335E-02
		4.09365740E-02	5.09647724E-02	6.09929708E-02	7.10211692E-02	8.10493676E-02

	60% TD of Soil	50% TD of Soil	40% TD Soil	30% TD Soil	20% TD Soil	10% TD Soil
Si	1.0034E-02	8.3617E-03	6.6893E-03	5.0170E-03	3.3447E-03	1.6723E-03
Al	2.2387E-03	1.8656E-03	1.4925E-03	1.1194E-03	7.4623E-04	3.7312E-04
Fe	5.1263E-04	4.2719E-04	3.4175E-04	2.5632E-04	1.7088E-04	8.5438E-05
Ca	6.3198E-04	5.2665E-04	4.2132E-04	3.1599E-04	2.1066E-04	1.0533E-04
K	6.1135E-04	5.0946E-04	4.0757E-04	3.0568E-04	2.0378E-04	1.0189E-04
Mg	4.1109E-04	3.4258E-04	2.7406E-04	2.0555E-04	1.3703E-04	6.8515E-05
Na	4.2591E-04	3.5493E-04	2.8394E-04	2.1296E-04	1.4197E-04	7.0985E-05
Ti	8.2025E-05	6.8354E-05	5.4683E-05	4.1013E-05	2.7342E-05	1.3671E-05
Mn	1.1108E-05	9.2567E-06	7.4053E-06	5.5540E-06	3.7027E-06	1.8513E-06
B11	1.3781E-05	1.1484E-05	9.1873E-06	6.8905E-06	4.5937E-06	2.2968E-06
O	2.5964E-02	2.1637E-02	1.7309E-02	1.2982E-02	8.6547E-03	4.3273E-03
H	2.6694E-02	3.3367E-02	4.0041E-02	4.6714E-02	5.3387E-02	6.0061E-02
O	1.3347E-02	1.6684E-02	2.0020E-02	2.3357E-02	2.6694E-02	3.0030E-02
N Tot	8.09772E-02	8.41645E-02	8.73519E-02	9.05393E-02	9.37267E-02	9.69141E-02
O Tot	3.9311E-02	3.8320E-02	3.7330E-02	3.6339E-02	3.5348E-02	3.4358E-02

Table A-5. Calculational data for a 50-g and a 10-g 20.3 × 20.3 × 15-cm (8 × 8 × 5-7/8-in.) filter.

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Z length of Filter Media (cm)	14.9225	
Y Length of Filter Media (cm)	16.51	
Area of One Sheet (cm2)	246.370475	
# of Sheets in Filter	32	
Total Area of Filter Media (cm2)	7883.8552	
MA Pu239(95%) Pu240 (5%)	239.1021	
MA Pu239	239.0521	
MA Pu240	240.0538	
MA Pu239(95%) Pu240 (5%)O2	271.1009	
Density of PuO2 (g/cm3)	11.46	
Grams of Pu (g)	50	10
Grams of PuO2 (g)	56.69	11.34

Gram Density of PuO2	1	2	3	4	5	6	7	8
Mass of PuO2 (g)	56.69	56.69	56.69	56.69	56.69	56.69	56.69	56.69
Volume of PuO2 (cm3)	56.69	28.35	18.90	14.17	11.34	9.45	8.10	7.09
N^{239}	2.1107E-03	4.2214E-03	6.3321E-03	8.4428E-03	1.0553E-02	1.2664E-02	1.4775E-02	1.6886E-02
N^{240}	1.1063E-04	2.2125E-04	3.3188E-04	4.4250E-04	5.5313E-04	6.6375E-04	7.7438E-04	8.8500E-04
N^{O}	4.4426E-03	8.8853E-03	1.3328E-02	1.7771E-02	2.2213E-02	2.6656E-02	3.1098E-02	3.5541E-02
N^{H}	6.0911E-02	5.5088E-02	4.9265E-02	4.3441E-02	3.7618E-02	3.1795E-02	2.5972E-02	2.0148E-02
N^{O}	3.0456E-02	2.7544E-02	2.4632E-02	2.1721E-02	1.8809E-02	1.5897E-02	1.2986E-02	1.0074E-02
$N^{O\ Tot}$	3.4898E-02	3.6429E-02	3.7960E-02	3.9491E-02	4.1022E-02	4.2553E-02	4.4084E-02	4.5615E-02
N^{Tot}	9.8031E-02	9.5960E-02	9.3889E-02	9.1818E-02	8.9747E-02	8.7676E-02	8.5605E-02	8.3534E-02
H/Pu Ratio	28.86	13.05	7.78	5.15	3.56	2.51	1.76	1.19
Mass of PuO2 (g)	11.34	11.34	11.34	11.34	11.34	11.34	11.34	11.34
Volume of PuO2 (cm3)	11.34	5.67	3.78	2.83	2.27	1.89	1.62	1.42
Thickness of PuO2 Layer Single Side of Media 50g PuO2	0.00719	0.00360	0.00240	0.00180	0.00144	0.00120	0.00103	0.00090
Thickness of PuO2 Layer Both Sides of Media 50 g PuO2	0.00360	0.00180	0.00120	0.00090	0.00072	0.00060	0.00051	0.00045
Thickness of PuO2 Layer Single Side of Media 10 g PuO2	0.00144	0.00072	0.00048	0.00036	0.00029	0.00024	0.00021	0.00018
Thickness of PuO2 Layer Both Sides of Media 10 g PuO2	0.00072	0.00036	0.00024	0.00018	0.00014	0.00012	0.00010	0.00009

Gram Density of PuO2	9	10	11	11.46
Mass of PuO2 (g)	56.69	56.69	56.69	56.69
Volume of PuO2 (cm3)	6.30	5.67	5.15	4.95
N^{239}	1.8996E-02	2.1107E-02	2.3218E-02	2.4188E-02
N^{240}	9.9563E-04	1.1063E-03	1.2169E-03	1.2678E-03
N^{O}	3.9984E-02	4.4426E-02	4.8869E-02	5.0913E-02
N^{H}	1.4325E-02	8.5019E-03	2.6787E-03	0.0000E+00
N^{O}	7.1626E-03	4.2510E-03	1.3393E-03	0.0000E+00
$N^{O\ Tot}$	4.7146E-02	4.8677E-02	5.0208E-02	5.0913E-02
N^{Tot}	8.1463E-02	7.9392E-02	7.7321E-02	7.6369E-02
	0.75	0.40	0.12	0.00
Mass of PuO2 (g)	11.34	11.34	11.34	11.34
Volume of PuO2 (cm3)	1.26	1.13	1.03	0.99
Thickness of PuO2 Layer Single Side of Media 50 g PuO2	0.00080	0.00072	0.00065	0.00063
Thickness of PuO2 Layer Both Sides of Media 50 g PuO2	0.00040	0.00036	0.00033	0.00031
Thickness of PuO2 Layer Single Side of Media 10 g PuO2	0.00016	0.00014	0.00013	0.00013
Thickness of PuO2 Layer Both Sides of Media 10 g PuO2	0.00008	0.00007	0.00007	0.00006

Gram Density of PuO2	1	2	3	4	5	6	7	8
Coordinates								
50 g Single Layer +x from Media of +x = 0.0381	0.04529	0.04170	0.04050	0.03990	0.03954	0.03930	0.03913	0.03900
10 g Single Layer +x from Media of +x = 0.0381	0.03954	0.03882	0.03858	0.03846	0.03839	0.03834	0.03831	0.03828
50 g Double Layer +x from Media of +x = 0.0	0.00360	0.00180	0.00120	0.00090	0.00072	0.00060	0.00051	0.00045
50 g Double Layer +x of Media	0.04170	0.03990	0.03930	0.03900	0.03882	0.03870	0.03861	0.03855
50 g Double Layer +x from Media of +x	0.04529	0.04170	0.04050	0.03990	0.03954	0.03930	0.03913	0.03900
50 g Double Layer +x of water channel for +x PuO2	0.51795	0.51615	0.51555	0.51525	0.51507	0.51495	0.51486	0.51480
10 g Double Layer +x from Media of +x = 0.0	0.00072	0.00036	0.00024	0.00018	0.00014	0.00012	0.00010	0.00009
10 g Double Layer +x of Media	0.03882	0.03846	0.03834	0.03828	0.03824	0.03822	0.03820	0.03819
10 g Double Layer +x from Media of +x	0.03954	0.03882	0.03858	0.03846	0.03839	0.03834	0.03831	0.03828
10 g Double Layer +x of water channel for +x PuO2	0.51507	0.51471	0.51459	0.51453	0.51449	0.51447	0.51445	0.51444

Gram Density of PuO2	9	10	11	11.46
Coordinates				
50 g Single Layer +x from Media of +x = 0.0381	0.03890	0.03882	0.03875	0.03873
10 g Single Layer +x from Media of +x = 0.0381	0.03826	0.03824	0.03823	0.03823
50 g Double Layer +x from Media of +x = 0.0	0.00040	0.00036	0.00033	0.00031
50 g Double Layer +x of Media	0.03850	0.03846	0.03843	0.03841
50 g Double Layer +x from Media of +x	0.03890	0.03882	0.03875	0.03873
50 g Double Layer +x of water channel for +x PuO2	0.51475	0.51471	0.51468	0.51466
10 g Double Layer +x from Media of +x = 0.0	0.00008	0.00007	0.00007	0.00006
10 g Double Layer +x of Media	0.03818	0.03817	0.03817	0.03816
10 g Double Layer +x from Media of +x	0.03826	0.03824	0.03823	0.03823
10 g Double Layer +x of water channel for +x PuO2	0.51443	0.51442	0.51442	0.51441

Table A-6. Calculational data for a 20.3 × 20.3 × 15.2-cm (8 × 8 × 6-in.) filter with reduced sized layers.

Z length of Filter Media (cm)	14.9225				
Y Length of Filter Media (cm)	16.51				
Area of One Sheet (cm2)	246.370475				
# of Sheets in Filter	32				
Total Area of Filter Media (cm2)	7883.8552				
% Normal Area of PuO_2 Layer	0.75	0.5	0.25	0.1	
Toatal Area PuO_2 is Spread Over (cm^2)	5912.8914	3941.9276	1970.9638	788.38552	
MA Pu239(95%) Pu240 (5%)	239.1021				
MA Pu239(95%) Pu240 (5%)O2	271.1009				
Density of PuO2 (g/cm3)	11.46				
Grams of Pu (g)	200	150			
Grams of PuO2 (g)	226.77	170.07			
Gram Density of PuO2	2				
Mass of PuO2 (g)	226.77				
Volume of PuO2 (cm3)	113.38				
N^{239}	4.2205E-03				
N^{240}	2.2213E-04				
N^{O}	8.8853E-03				
N^{H}	5.5088E-02				
N^{O}	2.7544E-02				
$N^{O\ Tot}$	3.6429E-02				
N^{Tot}	9.5960E-02				
H/Pu Ratio	13.05				
% of Filter Media Surface Covered	100	75	50	25	10
Thickness of PuO2 Layer Single Side of Media 200g PuO2	0.01438	0.01917554	0.02876	0.05753	0.14382
Coordinates of PuO_2 +x plane	0.05248	0.05728	0.06686	0.09563	0.18192

Table A-7. Graphite calculations.

$^{239}Pu(95\%)\ ^{240}Pu(5\%)\ O_2$-Graphite Mixture

Density of Graphite (g/cm^3)	2.25							
M_A Pu^{239}	239.0521							
M_A Pu^{240}	240.0538							
M_A $Pu^{239}(95\%)$ Pu^{240} (5%)	239.1021							
M_A $Pu^{239}(95\%)$ Pu^{240} $(5\%)O_2$	271.1009							
Density of PuO_2 (g/cm^3)	11.46							
Grams of Pu (g)	1500	200	400	600	800	1000		
Grams of PuO_2 (g)	1700.74	226.77	453.53	680.30	907.06	1133.83		
Volume of PuO_2 (cm^3)	148.41	19.79	39.58	59.36	79.15	98.94		
M_A Carbon Graphite	12.011							
N^C Pure Graphite	1.1281E-01							
0% Volume Fraction H_2O								
Not Ignoring the volume occupied by the PuO_2								
N^C	1.1273E-01							
Inside Radius of 55 Gal Drum (cm)	28.57							
Inside Hieght of 55 Gal Drum (cm)	85.09							
Vol of 55 Gal Drum (cm3)	218197.0512							
Mass of C in Drum (g)	490943.3653							
Radius of Graphite Sphere (cm)	37.3467							
1000 g Pu case								
Radius of PuO_2 in Graphite (cm)	5.0	10.0	15.0	20.0	25.0	30.0	35.0	37.3467
Vol of PuO_{2} - C at Radius (cm^3)	523.5988	4188.7902	14137.1669	33510.3216	65449.8469	113097.3355	179594.3800	218194.6815
N^{239}	4.5706E-03	5.7132E-04	1.6928E-04	7.1416E-05	3.6565E-05	2.1160E-05	1.3325E-05	1.0968E-05
N^{240}	2.3955E-04	2.9944E-05	8.8724E-06	3.7430E-06	1.9164E-06	1.1090E-06	6.9841E-07	5.7485E-07
N^O	9.6203E-03	1.2025E-03	3.5631E-04	1.5032E-04	7.6962E-05	4.4538E-05	2.8048E-05	2.3086E-05
N^C	9.1493E-02	1.1014E-01	1.1202E-01	1.1248E-01	1.1264E-01	1.1271E-01	1.1275E-01	1.1276E-01
N^{Tot}	1.059234E-01	1.119484E-01	1.125541E-01	1.127015E-01	1.127540E-01	1.127772E-01	1.127890E-01	1.127926E-01
Density of PuO_2 in Graphite (g/cm^3)	2.16545	0.27068	0.08020	0.03384	0.01732	0.01003	0.00631	0.00520

Graphite-H_2O and PuO_2 Cases

1000 g Pu							
Void Fraction in Graphite System	10%	20%	30%	40%	50%	60%	70%
Volume of Graphite System (cm^3)	242441.168	272746.314	311710.0732	363661.752	436394.1024	545492.6281	727323.5041
Radius of System (cm)	38.6803	40.2291	42.0602	44.2779	47.0522	50.6854	55.7865
N^C	1.0153E-01	9.0247E-02	7.8966E-02	6.7685E-02	5.6405E-02	4.5124E-02	3.3843E-02
N^{239}	1.1192E-05	9.9486E-06	8.7050E-06	7.4614E-06	6.2179E-06	4.9743E-06	3.7307E-06
N^{240}	5.8660E-07	5.2142E-07	4.5625E-07	3.9107E-07	3.2589E-07	2.6071E-07	1.9553E-07
$N^{O\ PuO2}$	2.35575E-05	2.094E-05	1.83225E-05	1.5705E-05	1.30875E-05	1.047E-05	7.85249E-06
N^H	6.6734E-03	1.3347E-02	2.0020E-02	2.6694E-02	3.3367E-02	4.0041E-02	4.6714E-02
$N^{O\ H2O}$	3.3367E-03	6.6734E-03	1.0010E-02	1.3347E-02	1.6684E-02	2.0020E-02	2.3357E-02
$N^{O\ Tot}$	3.3603E-03	6.6944E-03	1.0028E-02	1.3363E-02	1.6697E-02	2.0031E-02	2.3365E-02
N^{Tot}	1.115737E-01	1.102990E-01	1.090243E-01	1.077496E-01	1.064749E-01	1.052002E-01	1.039255E-01
H/Pu Ratio	596.26	1341.59	2299.86	3577.56	5366.35	8049.52	12521.48
C/Pu Ratio	9071.39	9071.39	9071.39	9071.39	9071.39	9071.39	9071.39

Graphite-H_2O and PuO_2 Cases in Drums

1000 g Pu Cases				
Void Fraction in Graphite System	10%	20%	30%	40%
Volume of Graphite System (cm^3)	196377.3461	174557.641	152737.9359	130918.2307
N^C	1.0153E-01	9.0247E-02	7.8966E-02	6.7685E-02
N^{239}	1.24357E-05	1.24357E-05	1.24357E-05	1.24357E-05
N^{240}	6.5178E-07	6.5178E-07	6.5178E-07	6.5178E-07
$N^{O\ PuO2}$	2.30855E-05	2.30855E-05	2.30855E-05	2.30855E-05
N^H	6.6734E-03	1.3347E-02	2.0020E-02	2.6694E-02
$N^{O\ H2O}$	3.3367E-03	6.6734E-03	1.0010E-02	1.3347E-02
$N^{O\ Tot}$	3.3598E-03	6.6965E-03	1.0033E-02	1.3370E-02
N^{Tot}	1.1157450E-01	1.1030374E-01	1.0903298E-01	1.0776222E-01
H/Pu Ratio	536.63	1073.27	1609.90	2146.54
C/Pu Ratio	8164.25	7257.11	6349.97	5442.83

Table A-8. Calculations for magnesium oxide.

^{239}Pu(95%) ^{240}Pu(5%) O_2-MgO Mixture

Density of MgO (g/cm^3)	3.58
M_A Pu^{239}(95%) Pu^{240} (5%)	239.1021
M_A Pu^{239}(95%) Pu^{240} (5%)O_2	271.1009
Density of PuO_2 (g/cm^3)	11.46
Grams of Pu (g)	1500
Grams of PuO_2 (g)	1700.74
Volume of PuO_2 (cm^3)	148.41
M_A MgO	40.3044
N^{Mg} MgO	5.3490E-02
N^{O} MgO	5.3490E-02

0% Volume Fraction H_2O

Not Ignoring the volume occupied by the PuO_2

Inside Radius of 55 Gal Drum (cm)	28.57
Inside Hieght of 55 Gal Drum (cm)	85.09
Vol of 55 Gal Drum (cm3)	218197.0512
Mass of MgO in Drum (g)	781145.4434
Radius of MgO Sphere (cm)	37.3467

Radius of PuO_2 in MgO (cm)	5.0	10.0	15.0	20.0	25.0	30.0	35.0	37.3467
Vol of PuO_2 at Radius (cm^3)	523.5988	4188.7902	14137.1669	33510.3216	65449.8469	113097.3355	179594.3800	218194.6815
N^{239}	6.8545E-03	8.5681E-04	2.5387E-04	1.0710E-04	5.4836E-05	3.1734E-05	1.9984E-05	1.6449E-05
N^{240}	3.6076E-04	4.5095E-05	1.3362E-05	5.6369E-06	2.8861E-06	1.6702E-06	1.0518E-06	8.6571E-07
$N^{O\ PuO2}$	1.4430E-02	1.8038E-03	5.3446E-04	2.2548E-04	1.1544E-04	6.6808E-05	4.2071E-05	3.4629E-05
N^{Mg}	3.8329E-02	5.1595E-02	5.2928E-02	5.3253E-02	5.3369E-02	5.3420E-02	5.3446E-02	5.3453E-02
N^{O}	3.8329E-02	5.1595E-02	5.2928E-02	5.3253E-02	5.3369E-02	5.3420E-02	5.3446E-02	5.3453E-02
N^{OTot}	5.2759E-02	5.3399E-02	5.3463E-02	5.3478E-02	5.3484E-02	5.3486E-02	5.3488E-02	5.3488E-02
N^{Tot}	9.830343E-02	1.058952E-01	1.066583E-01	1.068441E-01	1.069103E-01	1.069395E-01	1.069544E-01	1.069589E-01
Density of PuO_2 in MgO (g/cm^3)	3.24818	0.40602	0.12030	0.05075	0.02599	0.01504	0.00947	0.00779

MgO-H_2O and PuO_2 Cases

Void Fraction in MgO System	10%	20%	30%	40%	50%	60%	70%
Volume of MgO System (cm^3)	242441.168	272746.314	311710.0732	363661.752	436394.1024	545492.6281	727323.5041
Radius of System (cm)	38.6803	40.2291	42.0602	44.2779	47.0522	50.6854	55.7865
N^{Mg}	4.8141E-02	4.2792E-02	3.7443E-02	3.2094E-02	2.6745E-02	2.1396E-02	1.6047E-02
N^{O}	4.8141E-02	4.2792E-02	3.7443E-02	3.2094E-02	2.6745E-02	2.1396E-02	1.6047E-02
N^{239}	1.4804E-05	1.3159E-05	1.1514E-05	9.8690E-06	8.2242E-06	6.5794E-06	4.9345E-06
N^{240}	7.7913E-07	6.9256E-07	6.0599E-07	5.1942E-07	4.3285E-07	3.4628E-07	2.5971E-07
$N^{O\ PuO2}$	3.11654E-05	2.77025E-05	2.42397E-05	2.07769E-05	1.73141E-05	1.38513E-05	1.03885E-05
N^{H}	6.6734E-03	1.3347E-02	2.0020E-02	2.6694E-02	3.3367E-02	4.0041E-02	4.6714E-02
$N^{O\ H2O}$	3.3367E-03	6.6734E-03	1.0010E-02	1.3347E-02	1.6684E-02	2.0020E-02	2.3357E-02
$N^{O\ Tot}$	5.1509E-02	4.9493E-02	4.7477E-02	4.5462E-02	4.3446E-02	4.1430E-02	3.9414E-02
$N^{\ Tot}$	1.063386E-01	1.056456E-01	1.049526E-01	1.042596E-01	1.035666E-01	1.028735E-01	1.021805E-01
H/Pu Ratio	450.80	1014.30	1738.80	2704.80	4057.19	6085.79	9466.79
MgO/Pu Ratio	3251.98	3251.98	3251.98	3251.98	3251.98	3251.98	3251.98

Appendix B

Subsurface Disposal Area Soil Information

Appendix B

Subsurface Disposal Area Soil Information

The tables in this appendix show the soil composition and input parameters used in the computational models.

Table B-1. Analysis of soil sample from the spreading areas[a] at the Idaho National Engineering and Environmental Laboratory.

Oxide	Composition (wt%)
SiO_2	62.60
Al_2O_3	11.85
Fe_2O_3	4.25
CaO	3.68
K_2O	2.99
MgO	1.72
Na_2O	1.37
TiO_2	0.68
MnO_2	0.10
BaO	0.09
ZrO_2	0.05
B_2O_3	0.05
NiO	0.04
SrO	0.02
Cr_2O_3	0.02
Total oxide	**89.51**
Moisture	**7.5**

a. Data were taken from Callow et al. (1991).

Table B-2. Normalized soil sample from the spreading areas at the Idaho National Engineering and Environmental Laboratory.

Oxide	Composition (wt%)
SiO_2	69.936
Al_2O_3	13.239
Fe_2O_3	4.748
CaO	4.111
K_2O	3.340
MgO	1.922
Na_2O	1.531
TiO_2	0.760
MnO_2	0.112
BaO	0.101
ZrO_2	0.056
B_2O_3	0.056
NiO	0.044
SrO	0.022
Cr_2O_3	0.022
Total oxide	**100.0**

Table B-3. Compositions of soil from the Subsurface Disposal Area at the Idaho National Engineering and Environmental Laboratory.

Description	Element	Atoms/barn-cm
Wet soil	Si	1.0034E-02
	Al	2.2387E-03
	Fe	5.1263E-04
	Ca	6.3198E-04
	K	6.1135E-04
	Mg	4.1109E-04
	Na	4.2591E-04
	Ti	8.2025E-05
	Mn	1.1108E-05
	B-11	1.3781E-05
	H	2.6742E-02
	O	3.9335E-02
Dry soil	Si	1.0034E-02
	Al	2.2387E-03
	Fe	5.1263E-04
	Ca	6.3198E-04
	K	6.1135E-04
	Mg	4.1109E-04
	Na	4.2591E-04
	Ti	8.2025E-05
	Mn	1.1108E-05
	B-11	1.3781E-05
	O	2.5964E-02

Table B-4. Number densities used for cellulose ($C_6H_{10}O_5$ $\rho_{dens} = 1.45$ g/cm^3) material in the MCNP (RSIC 1997) code models.

Element	Nuclide Identification	Number Density (atoms/bn-cm)
Carbon	6012.50c	3.2310-02
Hydrogen	1001.50c	5.3851-02
Oxygen	8016.50c	2.6925-02

B.1 REFERENCE

Callow, R. A., L. E. Thompson, J. R. Weidner, C. A. Loehr, B. P. McGrail, and S. O. Bates, 1991, *In Situ Vitrification Application to Buried Waste Final Report of Intermediate Field Tests and Idaho National Engineering Laboratory*, EGG WTD-9807, Idaho National Engineering and Environmental Laboratory, EG&G Idaho, Idaho Falls, Idaho.

RSIC, 1997, "MCNP4-A General Monte Carlo N-Particle Transport Code, Version 4B," CCC-660/MCNP4B2, Radiation Shielding Information Center (contributed by Los Alamos National Laboratory), Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Appendix C

Sample of Monte Carlo N-Particle Transport Code Input Listings

Appendix C

Sample of Monte Carlo N-Particle Transport Code Input Listings

This appendix contains examples of the Monte Carlo N-Particle Transport Code input listings for various computational models used in this criticality safety study of the Subsurface Disposal Area for Operable Unit 7-13/14.

Case 8x8x5_13a:

2 x 1 x 2 array of 8 x 8 x 5 7/8-in glovebox high-efficiency particulate air (HEPA) filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters with full reflection around array with saturated Subsurface Disposal Area soil

```
Case 8x8x5_13a - Subsurface Disposal Area (SDA) Arrays of 8x8x5 filters
c
c 200g Pu per filter
c Soil Reflected
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modeled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 modeled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c    filter media cellulose sheets
c
c Pu modeled as 95% Pu239 5% Pu240
c
c  Cards 1-6 are the 200 g Pu loaded filters
c
1   1  1.13086-01  -2          u=1  $ Cellulose Media
2   4  9.5960-02   +2 -50       u=1  $ Layer of PuO2 & H2O
3   3  -1.0       +50         u=1  $ Water Between Fiber Media Sheets
4   0             +1 -3
                  lat=1  u=2
                  fill=-50:50 0:0 0:0
                 1 100r
5   0             -4 +5 -6 +7    $ Total Filter Media, Void And Pu
                  fill=2  u=3
6   2  -1.45      (+4:-5:+6:-7)  u=3  $ Plywood Frame
7   0             -10 +11 -12 +13 -8 +9
                  fill=3 u=4
8   5  8.1049574-02  (+10:-11:+12:-13:+8:-9) u=4  $Soil
9   0              -14 +15 -16 +17 -18 +19
                   fill=4 u=5 lat=1      $ Single Filter in Soil
10  0               -30 +31 -32 +33 -34 +35
                  fill=5 u=6
11  5  8.1049574-02  (+30:-31:+32:-33:+34:-35)  u=6
12  0               -400  fill=6
13  0               +400                  $ZIOW

1   px   0.0
2   px   0.0381    $ +x thickness of media
50   px   0.05248    $ Thickness of PuO2 and H2O
3   px   0.51435    $ 0.1875" Gap Due to 3/16" Mandrel
4   px    8.2550    $ +x Filter Media
5   px   -8.2550    $ -x Filter Media
6   py    8.2550    $ +y Filter Media
7   py   -8.2550    $ -y Filter Media
```

```
8    pz    7.46125    $ +z Filter
9    pz   -7.46125    $ -z Filter
10   px   10.1600     $ +x Plywood
11   px  -10.1600     $ -x Plywood
12   py   10.1600     $ +y Plywood
13   py  -10.1600     $ -y Plywood
14   px   10.66      $ +x Soil
15   px  -10.66      $ -x Soil
16   py   10.66      $ +y Soil
17   py  -10.66      $ -y Soil
18   pz    7.96125    $ +z Filter
19   pz   -7.96125    $ -z Filter
30   px   31.9799     $ +x Boundary of Array
31   px  -10.6599     $ -x Boundary of Array
32   py   10.6599     $ +y Boundary of Array
33   py  -10.6599     $ -y Boundary of Array
34   pz   23.8836     $ +z Boundary of Array
35   pz   -7.9611     $ -z Boundary of Array
400   so  200

mode n
imp:n 1 11r 0
c
c  Cellulose Filter Media
m1    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  Plywood Frame
m2    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  H2O
m3    1001.50c 2  8016.50c 1
c
c  PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4   94239.55c 4.2214-03  94240.50c 2.2125-04
      1001.50c 5.5088-02   8016.50c 3.6429-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
       20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
       11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
       5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print
```

Case12x12x6_2a:

2 x 1 x 2 array of 12 x 12 x 6-in.glovebox HEPA filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters – full reflection around array with saturated Subsurface Disposal Area soil

```
Case 12x12x6_2b - Subsurface Disposal Area (SDA)  Arrays of 12x12x6 Filters
c
c 200 g 239Pu per filter
c Soil reflected
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modeled inside water saturated soil
c
c 1.0 cm spacing between filters in each array
c
c PuO2 Modeled as a layer of PuO2 (3 g/cm3) and H2O (0.7382 g/cm3) on each of the
c    filter media cellulose sheets
c
c PuO2 Modeled as 95% Pu239 and 5% Pu240
c
c  Cards 1-7 are the 200 g Pu loaded filters
c
1   1   1.13086-01  -2          u=1  $ Cellulose Media
2   4   9.38887-02  +2 -50       u=1  $ Layer of PuO2
3   3   -1.0        +50          u=1  $ Water Between Fiber Media Sheets
4   0               +1 -3
                    lat=1  u=2
                    fill=-50:50 0:0 0:0
                    1 100r
5   0               -4 +5 -6 +7    $ Total Filter Media, Void And Pu
                    fill=2  u=3
6   2   -1.45       (+4:-5:+6:-7)  u=3  $ Plywood Frame
7   0               -10 +11 -12 +13 -8 +9
                    fill=3 u=4
8   5   8.1049574-02  (+10:-11:+12:-13:+8:-9) u=4  $Soil
9   0               -14 +15 -16 +17 -18 +19
                    fill=4 u=5 lat=1      $ Single Filter in Soil
10   0              -30 +31 -32 +33 -34 +35
                    fill=5 u=6
11   5   8.1049574-02  (+30:-31:+32:-33:+34:-35)  u=6
12   0               -400  fill=6
13   0               +400                    $ZIOW

1   px    0.0
2   px    0.0381     $ +x thickness of media
50   px    0.04175    $ Thickness of PuO2 and H2O
3   px    0.51435    $ 0.1875" Gap Due to 3/16" Mandrel
4   px   13.3350     $ +x Filter Media
5   px  -13.3350     $ -x Filter Media
6   py   13.3350     $ +y Filter Media
7   py  -13.3350     $ -y Filter Media
8   pz    7.46125    $ +z Filter
9   pz   -7.46125    $ -z Filter
10   px   15.24      $ +x Plywood
11   px  -15.24      $ -x Plywood
12   py   15.24      $ +y Plywood
13   py  -15.24      $ -y Plywood
14   px   15.74      $ Soil
15   px  -15.74      $ Soil
16   py   15.74      $ Soil
17   py  -15.74      $ Soil
18   pz    7.96125    $ Soil
```

```
19   pz   -7.96125    $ Soil
30   px   47.2199     $ +x Boundary of Array
31   px  -15.7399     $ -x Boundary of Array
32   py   15.7399     $ +y Boundary of Array
33   py  -15.7399     $ -y Boundary of Array
34   pz   23.7360     $ +z Boundary of Array
35   pz   -7.4611     $ -z Boundary of Array
400  so  200

mode n
imp:n 1 11r 0
c
c  Cellulose Filter Media
m1   6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  Plywood Frame
m2   6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  H2O
m3   1001.50c 2  8016.50c 1
c
c  PuO2 (3 g/cm3) and H2O (0.7382 g/cm3) In Thin Layer
m4  94239.55c 6.3321-03  94240.50c 3.3188-04
     1001.50c 4.9265-02   8016.50c 3.7960-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
       20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
       11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
        5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.04  0  0
c
print
```

Case 8x8x5_10:

2 x 1 x 2 array of 8 x 8 x5-7/8-in. glovebox HEPA filters – 200 g per filter – 0.0 cm edge-to-edge spacing between filters – full reflection around array with saturated Subsurface Disposal Area soil

```
Case 8x8x5_10 - Subsurface Disposal Area (SDA)  Arrays of 8x8x5 Filters
c
c 200g Pu per filter
c Soil Reflected
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modeled in water saturated soil
c 0.0 cm spacing between Filters in Array
c
c PuO2 Modeled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c    filter media cellulose sheets
c
c Pu modeled as 95% Pu239 5% Pu240
c
c  Cards 1-6 are the 200 g Pu loaded filters
c
1    1   1.13086-01  -2           u=1  $ Cellulose Media
2    4   9.5960-02   +2 -50       u=1  $ Layer of PuO2 & H2O
3    3   -1.0        +50          u=1  $ Water Between Fiber Media Sheets
4    0               +1 -3
                     lat=1  u=2
                     fill=-50:50 0:0 0:0
                     1 100r
5    0               -4 +5 -6 +7    $ Total Filter Media, Void And Pu
                     fill=2  u=3
6    2   -1.45       (+4:-5:+6:-7)  u=3  $ Plywood Frame
7    0               -10 +11 -12 +13 -8 +9
                     fill=3 u=4
8    5   8.1049574-02  (+10:-11:+12:-13:+8:-9) u=4  $Soil
9    0               -14 +15 -16 +17 -18 +19
                     fill=4 u=5 lat=1      $ Single Filter in Soil
10   0               -30 +31 -32 +33 -34 +35
                     fill=5 u=6
11   5   8.1049574-02  (+30:-31:+32:-33:+34:-35)  u=6
12   0               -400  fill=6
13   0               +400                 $ZIOW

1    px    0.0
2    px    0.0381     $ +x thickness of media
50   px    0.05248    $ Thickness of 200g Pu in PuO2 and H2O
51   px    0.04714    $ Thickness of 150g Pu in PuO2 and H2O
3    px    0.51435    $ 0.1875" Gap Due to 3/16" Mandrel
4    px    8.2550     $ +x Filter Media
5    px   -8.2550     $ -x Filter Media
6    py    8.2550     $ +y Filter Media
7    py   -8.2550     $ -y Filter Media
8    pz    7.46125    $ +z Filter
9    pz   -7.46125    $ -z Filter
10   px   10.1600     $ +x Plywood
11   px  -10.1600     $ -x Plywood
12   py   10.1600     $ +y Plywood
13   py  -10.1600     $ -y Plywood
14   px   10.1602     $ +x Soil
15   px  -10.1602     $ -x Soil
16   py   10.1602     $ +y Soil
```

```
17   py  -10.1602     $ -y Soil
18   pz    7.4614     $ +z Soil
19   pz   -7.4614     $ -z Soil
30   px   30.4805     $ +x Boundary of Array
31   px  -10.1601     $ -x Boundary of Array
32   py   10.1601     $ +y Boundary of Array
33   py  -10.1601     $ -y Boundary of Array
34   pz   22.3841     $ +z Boundary of Array
35   pz   -7.4613     $ -z Boundary of Array
400   so  200

mode n
imp:n 1 11r 0
c
c  Cellulose Filter Media
m1    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  Plywood Frame
m2    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  H2O
m3    1001.50c 2  8016.50c 1
c
c  PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4   94239.55c 4.2214-03  94240.50c 2.2125-04
     1001.50c 5.5088-02   8016.50c 3.6429-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
      20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
      11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
      5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print
```

Case 14e:

6 x 6 x 6 array of 8 x 8 x 5-7/8-in.glovebox HEPA filters – 50 g per filter – 1.0 cm edge-to-edge spacing between filters – full reflection around array with saturated Subsurface Disposal Area soil

```
Case 8x8x5_14e - Subsurface Disposal Area (SDA)  Arrays of 8x8x5 Filters
c
c 50g  Pu per filter
c Soil Reflected
c 6x6x6 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modeled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 Modeled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c    filter media cellulose sheets
c
c Pu modeled as 95% Pu239 5% Pu240
c
c  Cards 1-6 are the 50 g 239Pu loaded filters
c
1    1   1.13086-01  -2          u=1  $ Cellulose Media
2    4   9.5960-02   +2 -50       u=1  $ Layer of PuO2 & H2O
3    3   -1.0       +50          u=1  $ Water Between Fiber Media Sheets
4    0              +1 -3
                    lat=1  u=2
                    fill=-50:50 0:0 0:0
                   1 100r
5    0              -4 +5 -6 +7    $ Total Filter Media, Void And Pu
                    fill=2  u=3
6    2   -1.45      (+4:-5:+6:-7)  u=3  $ Plywood Frame
7    0              -10 +11 -12 +13 -8 +9
                    fill=3 u=4
8    5   8.1049574-02  (+10:-11:+12:-13:+8:-9) u=4  $Soil
9    0               -14 +15 -16 +17 -18 +19
                     fill=4 u=5 lat=1      $ Single Filter in Soil
10   0                -30 +31 -32 +33 -34 +35
                    fill=5 u=6
11   5   8.1049574-02  (+30:-31:+32:-33:+34:-35)  u=6
12   0                -400  fill=6
13   0                +400                 $ZIOW

1    px    0.0
2    px    0.0381     $ +x thickness of media
50   px    0.04170    $ Thickness of 200g Pu in PuO2 and H2O
3    px    0.51435    $ 0.1875" Gap Due to 3/16" Mandrel
4    px    8.2550     $ +x Filter Media
5    px   -8.2550     $ -x Filter Media
6    py    8.2550     $ +y Filter Media
7    py   -8.2550     $ -y Filter Media
8    pz    7.46125    $ +z Filter
9    pz   -7.46125    $ -z Filter
10   px   10.1600     $ +x Plywood
11   px  -10.1600     $ -x Plywood
12   py   10.1600     $ +y Plywood
13   py  -10.1600     $ -y Plywood
14   px   10.66       $ +x Soil
15   px  -10.66       $ -x Soil
16   py   10.66       $ +y Soil
17   py  -10.66       $ -y Soil
18   pz    7.96125    $ +z Soil
19   pz   -7.96125    $ -z Soil
```

```
30   px   74.6199     $ +x Boundary of Array
31   px  -53.2999     $ -x Boundary of Array
32   py   74.6199     $ +y Boundary of Array
33   py  -53.2999     $ -y Boundary of Array
34   pz   55.7286     $ +z Boundary of Array
35   pz  -39.8061     $ -z Boundary of Array
400   so  300

mode n
imp:n 1 11r 0
c
c  Cellulose Filter Media
m1    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  Plywood Frame
m2    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  H2O
m3    1001.50c 2  8016.50c 1
c
c  PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4   94239.55c 4.2214-03  94240.50c 2.2125-04
      1001.50c 5.5088-02   8016.50c 3.6429-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
       20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
       11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
       5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print
```

Case 8x8x5_15c:

2 x 1 x 2 array of 8 x 8 x5-7/8-in. glovebox HEPA filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters – soil and water filling gap space within filters - full reflection around array with saturated Subsurface Disposal Area soil

```
Case 8x8x5_15c - Subsurface Disposal Area (SDA)  Arrays of 8x8x5 Filters
c
c 200g Pu per filter
c Soil Reflected
c 2x2x3 Array of Filters - Cellulose to Represent CWS Filters
c Soil with varied water volume fraction (wvf) filling void in each filter
c Filters modeled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 Modeled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c    filter media cellulose sheets
c
c Pu modeled as 95% Pu239 5% Pu240
c
c 50% water density in 40% void in soil
c
c  Cards 1-7 are the 200 g Pu loaded filters
c
1   1   1.13086-01    -2            u=1  $ Cellulose Media
2   4   9.5960-02     +2 -50        u=1  $ Layer of PuO2 & H2O
3   6   6.099297-02   +50           u=1  $ Water Between Fiber Media Sheets
4   0               +1 -3
                    lat=1  u=2
                    fill=-50:50 0:0 0:0
                   1 100r
5   0               -4 +5 -6 +7    $ Total Filter Media, Void And Pu
                    fill=2  u=3
6   2   -1.45       (+4:-5:+6:-7)  u=3  $ Plywood Frame
7   0               -10 +11 -12 +13 -8 +9
                    fill=3 u=4
8   5   8.1049574-02  (+10:-11:+12:-13:+8:-9) u=4  $Soil
9   0                -14 +15 -16 +17 -18 +19
                     fill=4 u=5 lat=1      $ Single Filter in Soil
10   0                -30 +31 -32 +33 -34 +35
                    fill=5 u=6
11   5   8.1049574-02  (+30:-31:+32:-33:+34:-35)  u=6
12   0                -400  fill=6
13   0                +400                    $ZIOW

1   px    0.0
2   px    0.0381     $ +x thickness of media
50   px    0.05248    $ Thickness of 200g Pu in PuO2 and H2O
51   px    0.04714    $ Thickness of 150g Pu in PuO2 and H2O
3   px    0.51435    $ 0.1875" Gap Due to 3/16" Mandrel
4   px    8.2550     $ +x Filter Media
5   px   -8.2550     $ -x Filter Media
6   py    8.2550     $ +y Filter Media
7   py   -8.2550     $ -y Filter Media
8   pz    7.46125    $ +z Filter
9   pz   -7.46125    $ -z Filter
10   px   10.1600     $ +x Plywood
11   px  -10.1600     $ -x Plywood
12   py   10.1600     $ +y Plywood
13   py  -10.1600     $ -y Plywood
14   px   10.66      $ +x Soil
15   px  -10.66      $ -x Soil
16   py   10.66      $ +y Soil
```

```
17   py  -10.66       $ -y Soil
18   pz    7.96125    $ +z Filter
19   pz   -7.96125    $ -z Filter
30   px   31.9799     $ +x Boundary of Array
31   px  -10.6599     $ -x Boundary of Array
32   py   31.9799     $ +y Boundary of Array
33   py  -10.6599     $ -y Boundary of Array
34   pz   23.8836     $ +z Boundary of Array
35   pz  -23.8836     $ -z Boundary of Array
400   so  200

mode n
imp:n 1 11r 0
c
c  Cellulose Filter Media
m1    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  Plywood Frame
m2    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  H2O
m3    1001.50c 2  8016.50c 1
c
c  PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4   94239.55c 4.2214-03  94240.50c 2.2125-04
     1001.50c 5.5088-02   8016.50c 3.6429-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
      20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
      11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
      5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
c  Saturated Soil in Filters (50% out of 40% Void Volume Filled w H2O)
m6     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
      20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
      11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
       5011.56c 1.3781-05   1001.50c 1.3371-02   8016.50c 3.2649-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print
```

Case 8x8x5_16b:

2 x 1 x 2 array of 8 x 8 x5-7/8 glovebox HEPA filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters – soil and water filling gap space in filters - full reflection around array with saturated Subsurface Disposal Area soil

```
Case 8x8x5_16b - Subsurface Disposal Area (SDA)  Arrays of 8x8x5 Filters
c
c 200g Pu per filter
c Soil Reflected
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water with varied soil volume fraction (wvf) filling void in each filter
c
c 20% vol frac soil and 80% vol frac H2O in filters
c
c Filters modeled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 Modeled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c    filter media cellulose sheets
c
c Pu modeled as 95% Pu239 5% Pu240
c
c 100% water density in 40% void in soil
c
c  Cards 1-7 are the 200 g Pu loaded filters
c
1    1   1.13086-01    -2           u=1  $ Cellulose Media
2    4   9.5960-02     +2 -50       u=1  $ Layer of PuO2 & H2O
3    6   9.37267-02    +50          u=1  $ Water Between Fiber Media Sheets
4    0              +1 -3
                    lat=1  u=2
                    fill=-50:50 0:0 0:0
                    1 100r
5    0              -4 +5 -6 +7    $ Total Filter Media, Void And Pu
                    fill=2  u=3
6    2   -1.45      (+4:-5:+6:-7)  u=3  $ Plywood Frame
7    0              -10 +11 -12 +13 -8 +9
                    fill=3 u=4
8    5   8.1049574-02  (+10:-11:+12:-13:+8:-9) u=4  $Soil
9    0               -14 +15 -16 +17 -18 +19
                     fill=4 u=5 lat=1      $ Single Filter in Soil
10   0               -30 +31 -32 +33 -34 +35
                    fill=5 u=6
11   5   8.1049574-02  (+30:-31:+32:-33:+34:-35)  u=6
12   0                -400  fill=6
13   0                +400                  $ZIOW

1    px    0.0
2    px    0.0381     $ +x thickness of media
50   px    0.05248    $ Thickness of 200g Pu in PuO2 and H2O
51   px    0.04714    $ Thickness of 150g Pu in PuO2 and H2O
3    px    0.51435    $ 0.1875" Gap Due to 3/16" Mandrel
4    px    8.2550     $ +x Filter Media
5    px   -8.2550     $ -x Filter Media
6    py    8.2550     $ +y Filter Media
7    py   -8.2550     $ -y Filter Media
8    pz    7.46125    $ +z Filter
9    pz   -7.46125    $ -z Filter
10   px   10.1600     $ +x Plywood
11   px  -10.1600     $ -x Plywood
12   py   10.1600     $ +y Plywood
13   py  -10.1600     $ -y Plywood
```

```
14   px   10.66       $ +x Soil
15   px  -10.66       $ -x Soil
16   py   10.66       $ +y Soil
17   py  -10.66       $ -y Soil
18   pz    7.96125    $ +z Filter
19   pz   -7.96125    $ -z Filter
30   px   31.9799     $ +x Boundary of Array
31   px  -10.6599     $ -x Boundary of Array
32   py   10.6599     $ +y Boundary of Array
33   py  -10.6599     $ -y Boundary of Array
34   pz   23.8836     $ +z Boundary of Array
35   pz   -7.9611     $ -z Boundary of Array
400   so  200

mode n
imp:n 1 11r 0
c
c  Cellulose Filter Media
m1    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  Plywood Frame
m2    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  H2O
m3    1001.50c 2  8016.50c 1
c
c  PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4   94239.55c 4.2214-03  94240.50c 2.2125-04
      1001.50c 5.5088-02   8016.50c 3.6429-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
       20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
       11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
        5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
c  Water at 80% density with Soil at 20% density in Filters
m6     14000.50c 3.3447-03  13027.50c 7.4623-04  26000.55c 1.7088-04
       20000.50c 2.1066-04  19000.50c 2.0378-04  12000.50c 1.3703-04
       11023.50c 1.4197-04  22000.50c 2.7342-05  25055.50c 3.7027-06
        5011.56c 4.5937-06   1001.50c 5.3387-02   8016.50c 3.5348-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print
```

Case 8x8x5_17c:

2 x 1 x 2 array of 8 x 8 x5-7/8-in. glovebox HEPA filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters – B-10 included from soil in water in filters - full reflection around array with saturated Subsurface Disposal Area soil

```
Case 8x8x5_17c - Subsurface Disposal Area (SDA)  Arrays of 8x8x5 Filters
c
c 200g Pu per filter
c Reflected Array by Water Saturated Soil
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modeled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 Modeled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c    filter media cellulose sheets
c
c Pu modeled as 95% Pu239 5% Pu240
c
c B-10 included in water in filter
c 50% of B-10 from soil placed into water solution
c
c  Cards 1-6 are the 200 g Pu loaded filters
c
1   1   1.13086-01    -2           u=1  $ Cellulose Media
2   4   9.5960-02     +2 -50       u=1  $ Layer of PuO2 & H2O
3   6   1.00282316-01 +50          u=1  $ Water & B10 Between Fiber Media Sheets
4   0                +1 -3
                   lat=1  u=2
                   fill=-50:50 0:0 0:0
                   1 100r
5   0              -4 +5 -6 +7    $ Total Filter Media, Void And Pu
                   fill=2  u=3
6   2   -1.45      (+4:-5:+6:-7)  u=3  $ Plywood Frame
7   0              -10 +11 -12 +13 -8 +9
                   fill=3 u=4
8   5   8.1049574-02  (+10:-11:+12:-13:+8:-9) u=4  $Soil
9   0               -14 +15 -16 +17 -18 +19
                    fill=4 u=5 lat=1      $ Single Filter in Soil
10   0              -30 +31 -32 +33 -34 +35
                   fill=5 u=6
11   5   8.1049574-02  (+30:-31:+32:-33:+34:-35)  u=6
12   0               -400  fill=6
13   0               +400                  $ZIOW

1   px    0.0
2   px    0.0381    $ +x thickness of media
50   px    0.05248    $ Thickness of 200g Pu in PuO2 and H2O
51   px    0.04714    $ Thickness of 150g Pu in PuO2 and H2O
3   px    0.51435    $ 0.1875" Gap Due to 3/16" Mandrel
4   px    8.2550     $ +x Filter Media
5   px   -8.2550     $ -x Filter Media
6   py    8.2550     $ +y Filter Media
7   py   -8.2550     $ -y Filter Media
8   pz    7.46125    $ +z Filter
9   pz   -7.46125    $ -z Filter
10   px   10.1600     $ +x Plywood
11   px  -10.1600     $ -x Plywood
12   py   10.1600     $ +y Plywood
13   py  -10.1600     $ -y Plywood
14   px   10.66      $ +x Soil
15   px  -10.66      $ -x Soil
```

```
16   py   10.66       $ +y Soil
17   py  -10.66       $ -y Soil
18   pz    7.96125    $ +z Filter
19   pz   -7.96125    $ -z Filter
30   px   31.9799     $ +x Boundary of Array
31   px  -10.6599     $ -x Boundary of Array
32   py   10.6599     $ +y Boundary of Array
33   py  -10.6599     $ -y Boundary of Array
34   pz   23.8836     $ +z Boundary of Array
35   pz   -7.9611     $ -z Boundary of Array
400   so  200

mode n
imp:n 1 11r 0
c
c  Cellulose Filter Media
m1    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  Plywood Frame
m2    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  H2O
m3    1001.50c 2  8016.50c 1
c
c  PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4   94239.55c 4.2214-03  94240.50c 2.2125-04
      1001.50c 5.5088-02   8016.50c 3.6429-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
       20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
       11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
       5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
c  H2O and B-10  (50% available in SDA soil)
m6    1001.50c 6.6854-02  8016.50c 3.3427-02   5010.50c 1.3161-06
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print
```

Case 8x8x5_18c:

2 x 1 x 2 array of 8 x 8 x 5-7/8 glovebox HEPA filter– 200 g per filter – 1.0 cm edge-to-edge spacing between filters – gap spacing within filters reduced due to crushing of filter- full reflection around array with saturated Subsurface Disposal Area soil

```
Case 8x8x5_18c - Subsurface Disposal Area (SDA)  Arrays of 8x8x5 Filters
c
c 200g Pu per filter
c Soil Reflected
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modeled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 Modeled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c    filter media cellulose sheets
c
c Pu modeled as 95% Pu239 5% Pu240
c
c Gap spacing decreased to 25% of normal to account for compression
c
c  Cards 1-7 are the 200 g Pu loaded filters
c
1    1   1.13086-01  -2          u=1  $ Cellulose Media
2    4   9.5960-02   +2 -50       u=1  $ Layer of PuO2 & H2O
3    3   -1.0        +50         u=1  $ Water Between Fiber Media Sheets
4    0               +1 -3
                     lat=1  u=2
                     fill=-50:50 0:0 0:0
                    1 100r
5    0               -4 +5 -6 +7    $ Total Filter Media, Void And Pu
                     fill=2  u=3
6    2   -1.45       (+4:-5:+6:-7)  u=3  $ Plywood Frame
7    0               -10 +11 -12 +13 -8 +9
                     fill=3 u=4
8    5   8.1049574-02  (+10:-11:+12:-13:+8:-9) u=4  $Soil
9    0                -14 +15 -16 +17 -18 +19
                      fill=4 u=5 lat=1      $ Single Filter in Soil
10   0                 -30 +31 -32 +33 -34 +35
                     fill=5 u=6
11   5   8.1049574-02  (+30:-31:+32:-33:+34:-35)  u=6
12   0                 -400  fill=6
13   0                 +400                   $ZIOW

1    px    0.0
2    px    0.0381     $ +x thickness of media
50   px    0.05248    $ Thickness of 200g Pu in PuO2 and H2O
3    px    0.157556   $ 50% of Normal Gap Due Compression
4    px    2.52090    $ +x Filter Media
5    px   -2.52090    $ -x Filter Media
6    py    8.2550     $ +y Filter Media
7    py   -8.2550     $ -y Filter Media
8    pz    7.46125    $ +z Filter
9    pz   -7.46125    $ -z Filter
10   px    4.4259     $ +x Plywood
11   px   -4.4259     $ -x Plywood
12   py    10.1600    $ +y Plywood
13   py   -10.1600    $ -y Plywood
14   px    4.93       $ +x Soil
15   px   -4.93       $ -x Soil
16   py    10.66      $ +y Soil
```

```
17   py  -10.66       $ -y Soil
18   pz    7.96125    $ +z Filter
19   pz   -7.96125    $ -z Filter
30   px   14.7899     $ +x Boundary of Array
31   px   -4.9299     $ -x Boundary of Array
32   py   10.6599     $ +y Boundary of Array
33   py  -10.6599     $ -y Boundary of Array
34   pz   23.8836     $ +z Boundary of Array
35   pz   -7.9611     $ -z Boundary of Array
400  so  200

mode n
imp:n 1 11r 0
c
c  Cellulose Filter Media
m1    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  Plywood Frame
m2    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  H2O
m3    1001.50c 2  8016.50c 1
c
c  PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4   94239.55c 4.2214-03  94240.50c 2.2125-04
     1001.50c 5.5088-02   8016.50c 3.6429-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
      20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
      11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
      5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.4 0 0
c
print
```

Case 8x8x5_20a:

2 x 1 x 2 array of 8 x 8 x 5-7/8-in. glovebox HEPA filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters – area over filter sheets that PuO2 is dispersed is reduced - full reflection around array with saturated Subsurface Disposal Area soil

```
Case 8x8x5_20a - Subsurface Disposal Area (SDA)  Arrays of 8x8x5 Filters
c
c 200g Pu per filter
c Soil Reflected
c 2x1x2 Array of Filters - Cellulose to Represent CWS Filters
c Water filling void in each filter
c Filters modeled in water saturated soil
c 1.0 cm spacing between Filters in Array
c
c PuO2 Modeled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c    filter media cellulose sheets
c
c Pu modeled as 95% Pu239 5% Pu240
c
c In this case the PuO2 is spread over a reduced area 75% of total filter area
c   thus effectively increasing the thickness of the layer of PuO2
c
c  Cards 1-9 are the 200 g Pu loaded filters Top Row
c
1    1   1.13086-01  -2           u=1  $ Cellulose Media
2    4   9.5960-02   +2 -55 -50    u=1  $ Layer of PuO2 & H2O
3    3   -1.0        +2 +55 -50    u=1  $ Layer of H2O
4    3   -1.0        +50           u=1  $ Water Between Fiber Media Sheets
5    0               +1 -3
                     lat=1  u=2
                     fill=-50:50 0:0 0:0
                    1 100r
6    0               -4 +5 -6 +7    $ Total Filter Media, Void And Pu
                     fill=2  u=3
7    2   -1.45       (+4:-5:+6:-7)  u=3  $ Plywood Frame
8    0               -10 +11 -12 +13 -8 +9
                     fill=3 u=4
9    5   8.1049574-02  (+10:-11:+12:-13:+8:-9) u=4  $Soil
c
c  Cards 10-18 are the 200 g Pu loaded filters Bottom Row
c
10   1   1.13086-01  -2           u=5  $ Cellulose Media
11   4   9.5960-02   +2 +56 -50    u=5  $ Layer of PuO2 & H2O
12   3   -1.0        +2 -56 -50    u=5  $ Layer of H2O
13   3   -1.0        +50           u=5  $ Water Between Fiber Media Sheets
14   0               +1 -3
                     lat=1  u=6
                     fill=-50:50 0:0 0:0
                    5 100r
15   0               -4 +5 -6 +7    $ Total Filter Media, Void And Pu
                     fill=6  u=7
16   2   -1.45       (+4:-5:+6:-7)  u=7  $ Plywood Frame
17   0               -10 +11 -12 +13 -8 +9
                     fill=7 u=8
18   5   8.1049574-02  (+10:-11:+12:-13:+8:-9) u=8  $Soil
19   0                 -14 +15 -16 +17 -18 +19
                     lat=1 u=9
                     fill=0:1  0:1  -1:1
                       8 8 4 4
                       8 8 4 4
                       8 8 4 4
20   0                 -30 +31 -32 +33 -34 +35 fill=9 u=10
21   5   8.1049574-02  +30:-31:+32:-33:+34:-35 u=10
```

```
22   0              -400  fill=10
23   0              +400                   $ZIOW

1    px    0.0
2    px    0.0381     $ +x thickness of media
50   px    0.05728    $ Thickness of 200g Pu in PuO2 and H2O
3    px    0.51435    $ 0.1875" Gap Due to 3/16" Mandrel
4    px    8.2550     $ +x Filter Media
5    px   -8.2550     $ -x Filter Media
6    py    8.2550     $ +y Filter Media
55   py    4.1275     $ +y plane to restrict area
56   py   -4.1275     $ -y plane to restrict area
7    py   -8.2550     $ -y Filter Media
8    pz    7.46125    $ +z Filter
9    pz   -7.46125    $ -z Filter
10   px   10.1600     $ +x Plywood
11   px  -10.1600     $ -x Plywood
12   py   10.1600     $ +y Plywood
13   py  -10.1600     $ -y Plywood
14   px   10.66       $ +x Soil
15   px  -10.66       $ -x Soil
16   py   10.66       $ +y Soil
17   py  -10.66       $ -y Soil
18   pz    7.96125    $ +z Filter
19   pz   -7.96125    $ -z Filter
30   px   31.9799     $ +x Boundary of Array
31   px  -10.6599     $ -x Boundary of Array
32   py   10.6599     $ +y Boundary of Array
33   py  -10.6599     $ -y Boundary of Array
34   pz   23.8836     $ +z Boundary of Array
35   pz   -7.9611     $ -z Boundary of Array
400   so  200

mode n
imp:n 1 21r 0
c
c  Cellulose Filter Media
m1    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  Plywood Frame
m2    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  H2O
m3    1001.50c 2  8016.50c 1
c
c  PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4   94239.55c 4.2214-03  94240.50c 2.2125-04
     1001.50c 5.5088-02   8016.50c 3.6429-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
      20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
      11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
      5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
kcode 4004 1.0 50  200
c
c Source for Array
ksrc 0.4 0 0
c
print
```

Case 12x12x6_3g

Single 12 x 12 x 6-in. glovebox HEPA Filters – 200 g per filter – 1.0 cm edge-to-edge spacing between filters – filter overloaded with 1,000g of PuO2 - full reflection around filter with saturated Subsurface Disposal Area soil

```
Case 12x12x6_3g - Subsurface Disposal Area (SDA)  Single Overloaded Filters
c
c 900 g Pu in filter
c Single Filters - Cellulose to Represent CWS Filters
c Water filling void in filter
c Filter modeled inside water saturated soil
c
c PuO2 Modeled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c    filter media cellulose sheets
c
c PuO2 Modeled as 95% Pu239 and 5% Pu240
c
c  Cards 1-7 are the 900 g Pu loaded filter
c
1    1   1.13086-01  -2          u=1  $ Cellulose Media
2    4   9.59596-02  +2 -50       u=1  $ Layer of PuO2
3    3   -1.0       +50          u=1  $ Water Between Fiber Media Sheets
4    0              +1 -3
                    lat=1  u=2
                    fill=-50:50 0:0 0:0
                    1 100r
5    0              -4 +5 -6 +7    $ Total Filter Media, Void And Pu
                    fill=2  u=3
6    2   -1.45      (+4:-5:+6:-7)  u=3  $ Plywood Frame
7    0              -10 +11 -12 +13 -8 +9
                    fill=3 u=4
8    5   8.1049574-02  (+10:-11:+12:-13:+8:-9) u=4  $Soil
9    0               -400  fill=4
10   0                +400                  $ZIOW

1    px    0.0
2    px    0.0381     $ +x thickness of media
50   px    0.06275    $ Thickness of PuO2 and H2O
3    px    0.51435    $ 0.1875" Gap Due to 3/16" Mandrel
4    px   13.3350     $ +x Filter Media
5    px  -13.3350     $ -x Filter Media
6    py   13.3350     $ +y Filter Media
7    py  -13.3350     $ -y Filter Media
8    pz    7.46125    $ +z Filter
9    pz   -7.46125    $ -z Filter
10   px   15.24       $ +x Plywood
11   px  -15.24       $ -x Plywood
12   py   15.24       $ +y Plywood
13   py  -15.24       $ -y Plywood
400  so  200

mode n
imp:n 1 8r 0
c
c  Cellulose Filter Media
m1   6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  Plywood Frame
m2   6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  H2O
m3   1001.50c 2  8016.50c 1
```

```
c
c  PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4  94239.55c 4.2214-03  94240.50c 2.2125-04
     1001.50c 5.5088-02   8016.50c 3.6429-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
       20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
       11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
        5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0.04  0  0
c
print
```

Case drums_1a

2 x 2 x 2 array of drums – each drum housing a single 8 x 8 x 5-7/8-in. filter containing 200 g PuO_2 per filter – filters offset in drums to increase reactivity – full reflection with saturated Subsurface Disposal Area soil outside array of drums and within remaining void in drums

```
Case drums_1a - Subsurface Disposal Area (SDA) 55 Gal Drums Containing
c   HEPA Filters  8" x 8" x5 7/8" Filters
c
c 200g Pu per filter
c Soil Reflected
c 2x2x2 Array of Drums - Cellulose to Represent CWS Filters
c Water filling void in each filter
c
c Drums Touching
c
c PuO2 Modeled as a layer of PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) on each of the
c    filter media cellulose sheets
c
c Pu modeled as 95% Pu239 5% Pu240
c
c  Cards 1-6 are the 200 g Pu loaded filters
c
1   1   1.13086-01  -2          u=1  $ Cellulose Media
2   4   9.5960-02   +2 -50       u=1  $ Layer of PuO2 & H2O
3   3   -1.0        +50          u=1  $ Water Between Fiber Media Sheets
4   0               +1 -3
                    lat=1  u=2
                    fill=-50:50 0:0 0:0
                    1 100r
5   0               -4 +5 -6 +7    $ Total Filter Media, Void And Pu
                    fill=2  u=3
6   2   -1.45       (+4:-5:+6:-7)  u=3  $ Plywood Frame
7   0               -10 +11 -12 +13 -8 +9  trcl=(16.4  0 35.078)
                    fill=3 u=4
8   5   8.1049574-02  #7            u=4  $Soil
9   0                -14 -16 +17
                     fill=4 u=5       $ Single Filter in Drum
10  6   -7.92        +14:+16:-17 u=5      $ Carbon Steel Drum
11  0                -15 -18 +19
                     fill=5 u=6
12                   like 11 but trcl=1  u=6
13                   like 11 but trcl=2  u=6
14                   like 11 but trcl=3  u=6
15                   like 11 but trcl=4  u=6
16                   like 11 but trcl=5  u=6
17                   like 11 but trcl=6  u=6
18                   like 11 but trcl=7  u=6
19  5   8.1049574-02  #11 #12 #13 #14 #15 #16 #17 #18 u=6
20  0                 -400 fill=6
21  0                 +400                 $ZIOW

1   px   0.0
2   px   0.0381     $ +x thickness of media
50  px   0.05248    $ Thickness of PuO2 and H2O
3   px   0.51435    $ 0.1875" Gap Due to 3/16" Mandrel
4   px   8.2550     $ +x Filter Media
5   px   -8.2550    $ -x Filter Media
6   py   8.2550     $ +y Filter Media
7   py   -8.2550    $ -y Filter Media
8   pz   7.46125    $ +z Filter
9   pz   -7.46125   $ -z Filter
```

```
10   px   10.1600     $ +x Plywood
11   px  -10.1600     $ -x Plywood
12   py   10.1600     $ +y Plywood
13   py  -10.1600     $ -y Plywood
14   cz   28.575      $ Inside Radius of Drum
15   cz   28.727      $ Outside Radius of Drum
16   pz   42.545      $ +z Inside of Drum
17   pz  -42.545      $ -z Inside of Drum
18   pz   42.695      $ +z Outside of Drum
19   pz  -42.695      $ -z Outside of Drum
400   so  400

mode n
imp:n 1 19r 0
c
c  Cellulose Filter Media
m1    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  Plywood Frame
m2    6012.50c 3.2310-02  1001.50c 5.3851-02  8016.50c 2.6925-02
c
c  H2O
m3    1001.50c 2  8016.50c 1
c
c  PuO2 (2 g/cm3) and H2O (0.82548 g/cm3) In Thin Layer
m4   94239.55c 4.2214-03  94240.50c 2.2125-04
      1001.50c 5.5088-02   8016.50c 3.6429-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m5     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
       20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
       11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
       5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
c Carbon Steel Drum (Density 7.93 g/cm3)
m6     6012.50c  1
c
c
tr1*  57.5     0    0     180  90 90   90 180 90    90 90 0
tr2*  28.575  49.9  0      90 180 90    0  90 90    90 90 0
tr3*  28.575 -49.9  0      90   0 90  180  90 90    90 90 0
tr4*  0       0    85.4   0   90 90   90   0 90    90 90 180
tr5*  57.5     0    85.4  180  90 90   90 180 90    90 90 180
tr6*  28.575  49.9  85.4   90 180 90    0  90 90    90 90 180
tr7*  28.575 -49.9  85.4   90   0 90  180  90 90    90 90 180
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 16.9 0 41.9
c
print
```

Case graphite_1h
1,000 g of plutonium combined with dry graphite in spherical form – fully reflected

```
Case graphite_1h - Subsurface Disposal Area (SDA)  PuO2 in Graphite
c 1000 g Pu from a single drum
c Soil Reflected
c
c PuO2 Modeled as PuO2 dispersed in graphite.
c
c Pu modeled as 95% Pu239 5% Pu240
c
c PuO2 dipsered over a 37.3467 cm radius sphere of graphite
c 0.007 g/cc of PuO2 in volume modeled
c
c
c
1   1   1.127926-01   -2          $ PuO2 and Graphite
2   3   8.1049574-02  +2 -3       $ Water saturated soil
3   0                 +3          $ ZIOW

1   so   35.0      $ PuO2 in Graphite
2   so   37.3467   $ Graphite
3   so   150.0     $ Soil (40% vf water saturated)

mode n
imp:n 1 1 0
c
c  PuO2 in Graphite
m1   6012.50c 1.1276-01  94239.55c 1.0968-05  94240.50c 5.7485-07
     8016.50c 2.3086-05
c
c  Graphite
m2   6012.50c 1.12808-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m3    14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
      20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
      11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
      5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0  0  0
c
print
```

Case graphite-2b

1,000 g plutonium combined with graphite and water in spherical form – fully reflected

```
Case graphite_2b - Subsurface Disposal Area (SDA)  PuO2 in Graphite and H2O
c 1000 g Pu from a single drum
c Soil Reflected
c
c PuO2 Modeled as PuO2 dispersed in graphite and water.
c
c Pu modeled as 95% Pu239 5% Pu240
c
c PuO2 dispsered over a 40.23 cm radius sphere of graphite and water
c 20% volume fraction modeled in graphite filled with water
c
c
c
1   1   1.102990-01   -1            $ PuO2, H2O, Graphite
2   3   8.1049574-02  +1 -2         $ Water saturated soil
3   0                 +2            $ ZIOW

1   so    40.2291    $ PuO2 in Graphite
2   so   300.0       $ Soil (40% vf water saturated)

mode n
imp:n 1 1 0
c
c  PuO2 in Graphite and H2O
m1    6012.50c 9.0247-02  94239.55c 9.9486-06  94240.50c 5.2142-07
      8016.50c 6.6944-03   1001.50c 1.3347-02
c
c  Graphite
m2    6012.50c 1.12808-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m3     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
       20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
       11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
       5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0  0  0
c
print
```

Case graphite_4a1e

Drum containing PuO_2, graphite, and water – full reflection around drum

```
Case graphite_4a1e - Subsurface Disposal Area (SDA)  PuO2, H2O & Graphite in Drum
c 1000 g Pu in a single drum
c Soil Reflected
c
c PuO2 Modeled as PuO2 dispersed in 80% density graphite.
c Remaining 20% volume fraction filled with water
c
c Pu modeled as 95% Pu239 5% Pu240
c
c PuO2 dispsered over entire volume of drum
c Single overloaded drum
c
c
c
1   1   1.1030220-01  -1 -2 +3   u=1   $ PuO2(1000 g Pu), H2O & Graphite
2   2   -7.82         +1:+2:-3   u=1
3   0               -4 -5 +6  fill=1 u=2
4   3   8.1049574-02  +4:+5:-6  u=2    $ Water saturated soil
5   0               -13 +14 -15 +16 -17 +18  fill=2 u=3
6   3   8.1049574-02  +13:-14:+15:-16:+17:-18  u=3    $ Water saturated soil
7   0               -20 +21 -22 +23 -24 +25  fill=3
8   0               +20:-21:+22:-23:+24:-25    $ ZIOW

1    cz    28.575     $ Inside radius of drum
2    pz    42.545     $ Inside height +z
3    pz   -42.545     $ Inside height -z
4    cz    28.727     $ Oustide radius of drum 0.152 cm thick wall
5    pz    42.695     $ Outside height of drum 0.15 cm thick wall
6    pz   -42.695     $ Outside height of drum 0.15 cm thick wall
7    px    28.73
8    px   -28.73
9    py    28.73
10   py   -28.73
11   pz    42.70
12   pz   -42.70
13   px    28.7299
14   px   -28.7299
15   py    28.7299
16   py   -28.7299
17   pz    42.6999
18   pz   -42.6999
20   px   200
21   px  -200
22   py   200
23   py  -200
24   pz   250
25   pz  -170

mode n
imp:n 1 6r 0
c
c  PuO2, H2O, 80% Density Graphite (1000 g Pu in single drum)
m1    6012.50c 9.0247-02  94239.55c 1.0968-05  94240.50c 5.7484-07
      8016.50c 6.6965-03   1001.50c 1.3347-02
c
c  Carbon Steel
m2    6012.50c 1.96E-03  26000.55c  8.390-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
```

```
m3     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
       20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
       11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
       5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0  0  0
c
print
```

Case mgo_1h:

1,500 g PuO_2 and dry MgO in spherical form – fully reflected

```
Case mgo_1h - Subsurface Disposal Area (SDA)  PuO2 in MgO
c 1500 g Pu from a single drum
c Soil Reflected
c
c PuO2 Modeled as PuO2 dispersed in MgO.
c
c Pu modeled as 95% Pu239 5% Pu240
c
c PuO2 dispspered over a 35.0 cm radius sphere of MgO
c 0.0077 g/cc of PuO2 in volume modeled
c
c
c
c
1   1   1.069589-01   -1          $ PuO2 and MgO
2   3   8.1049574-02   +1 -2       $ Water saturated soil
3   0                  +2          $ ZIOW

1   so   37.3467    $ PuO2 in MgO
2   so   150.0      $ Soil (40% vf water saturated)

mode n
imp:n 1 1r 0
c
c  PuO2 in MgO
m1    12000.50c 5.3453-02  94239.55c 1.6449-05  94240.50c 8.6571-07
      8016.50c 5.3488-02
c
c  MgO
m2   12000.50c 5.3453-02   8016.50c  5.3453-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m3     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
      20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
      11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
      5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0  1  0
c
print
```

Case mgo_2b:

1,500 g PuO2, MgO, and water in spherical form, fully reflected

```
Case mgo_2b - Subsurface Disposal Area (SDA)  PuO2 in MgO and H2O
c 1500 g Pu from a single drum
c Soil Reflected
c
c PuO2 Modeled as PuO2 dispersed in MgO and water.
c
c Pu modeled as 95% Pu239 5% Pu240
c
c PuO2 dispsered over a 40.23 cm radius sphere of graphite and water
c 20% volume fraction modeled in MgO filled with water
c
c
c
1   1   1.056456-01   -1             $ PuO2, H2O, MgO
2   3   8.1049574-02  +1 -2           $ Water saturated soil
3   0                 +2             $ ZIOW

1   so   40.2291   $ PuO2 in MgO
2   so   300.0     $ Soil (40% vf water saturated)

mode n
imp:n 1 1 0
c
c  PuO2 in MgO and H2O
m1   12000.50c 4.2792-02  94239.55c 1.3159-05  94240.50c 6.9256-07
     8016.50c 4.9493-02   1001.50c 1.3347-02
c
c  MgO
m2   12000.50c 5.3453-02   8016.50c  5.3453-02
c
c  Saturated Soil in SDA (40% Void Volume Filled w H2O)
m3     14000.50c 1.0034-02  13027.50c 2.2387-03  26000.55c 5.1263-04
      20000.50c 6.3198-04  19000.50c 6.1135-04  12000.50c 4.1109-04
      11023.50c 4.2591-04  22000.50c 8.2025-05  25055.50c 1.1108-05
      5011.56c 1.3781-05   1001.50c 2.6742-02   8016.50c 3.9335-02
c
kcode 4000 1.0 50 200
c
c Source for Array
ksrc 0  0  0
c
print
```